NAVAL POSTGRADUATE SCHOOL

MONTEREY, CALIFORNIA

THESIS

NAVAL FUEL MANAGEMENT SYSTEM (NFMS): A DECISION SUPPORT SYSTEM FOR A LIMITED RESOURCE

by

John E. Fallon

September 2010

Thesis Co-Advisors:	Daniel Dolk Kenneth Doerr

THIS PAGE INTENTIONALLY LEFT BLANK

REPORT DOCUMENTATION PAGE	*Form Approved OMB No. 0704-0188*

1. AGENCY USE ONLY *(Leave blank)*	**2. REPORT DATE** September 2010	**3. REPORT TYPE AND DATES COVERED** Master's Thesis

4. TITLE AND SUBTITLE Naval Fuel Management System (NFMS): A Decision Support System for a Limited Resource

5. FUNDING NUMBERS

6. AUTHOR(S) John E. Fallon

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Naval Postgraduate School
Monterey, CA 93943-5000

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING /MONITORING AGENCY NAME(S) AND ADDRESS(ES)
N/A

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government. IRB Protocol number _______N/A_______.

12a. DISTRIBUTION / AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited

12b. DISTRIBUTION CODE

13. ABSTRACT (maximum 200 words)

The fuel planning for U.S. naval operations at sea is reactive and relies upon pen and paper calculations. Decisions on where and when to refuel are complex and need a Decision Support System (DSS) to help planners maximize the benefits of the limited fuel resource. This thesis defines requirements and outlines a feasible design to develop a Naval Fuel Management System (NFMS). The variables that fuel planning rely upon are not just ship course and speed, but also the weather at the time a ship travels through a particular area. The most efficient plant configuration plays a factor in the fuel plan as well. Additionally, there are numerous ports and oilers available at any given time. Up-to-date accurate weather forecast databases are available, predicting currents and winds, which will affect the ship in the future. Fuel burn charts have been developed for each ship class outlining the most efficient plant configuration for given speeds. Transportation analysis has shown that an optimal path exists for this class of complex problems. By combining these technologies into one system, an application can be developed to accurately plan fueling operations in the future, making Navy refueling more efficient.

14. SUBJECT TERMS Naval Fuel Management System, NFMS, fuel, refuel, shortest path, service oriented architecture, SOA, valued information at the right time, VIRT, linear programming

15. NUMBER OF PAGES 97

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	**18. SECURITY CLASSIFICATION OF THIS PAGE**	**19. SECURITY CLASSIFICATION OF ABSTRACT**	**20. LIMITATION OF ABSTRACT**
Unclassified	Unclassified	Unclassified	UU

NSN 7540-01-280-5500 Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. 239-18

THIS PAGE INTENTIONALLY LEFT BLANK

Approved for public release; distribution is unlimited

NAVAL FUEL MANAGEMENT SYSTEM (NFMS): A DECISION SUPPORT SYSTEM FOR A LIMITED RESOURCE

John E. Fallon
Lieutenant, United States Navy
B.S., Old Dominion University, 2001

Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN INFORMATION TECHNOLOGY MANAGEMENT

from the

NAVAL POSTGRADUATE SCHOOL
September 2010

Author: John E. Fallon

Approved by: Daniel Dolk
Thesis Co-Advisor

Kenneth Doerr
Co-Advisor

Dr. Dan Boger
Chairman, Department of Information Sciences

THIS PAGE INTENTIONALLY LEFT BLANK

ABSTRACT

The fuel planning for U.S. naval operations at sea is reactive and relies upon pen and paper calculations. Decisions on where and when to refuel are complex and need a Decision Support System (DSS) to help planners maximize the benefits of the limited fuel resource. This thesis defines requirements and outlines a feasible design to develop a Naval Fuel Management System (NFMS). The variables that fuel planning rely upon are not just ship course and speed, but also the weather at the time a ship travels through a particular area. The most efficient plant configuration plays a factor in the fuel plan as well. Additionally, there are numerous ports and oilers available at any given time. Up-to-date accurate weather forecast databases are available, predicting currents and winds, which will affect the ship in the future. Fuel burn charts have been developed for each ship class outlining the most efficient plant configuration for given speeds. Transportation analysis has shown that an optimal path exists for this class of complex problems. By combining these technologies into one system, an application can be developed to accurately plan fueling operations in the future, making Navy refueling more efficient.

THIS PAGE INTENTIONALLY LEFT BLANK

TABLE OF CONTENTS

LIST OF FIGURES

THIS PAGE INTENTIONALLY LEFT BLANK

LIST OF TABLES

THIS PAGE INTENTIONALLY LEFT BLANK

EXECUTIVE SUMMARY

This thesis will focus on identifying the requirements and generating a design for a Decision Support System (DSS) to manage the Navy's fuel usage on ships. Current practices to determine fueling points utilize calculations done on paper using paper burn charts, and an oversimplified model, the Position of Intended Movement (PIM) as input variables. Fueling arrangements are made either on a periodic basis or, at most, one or two weeks before the intended refueling date. The periodic refueling schedule wastes fuel both in reaching the refueling points, and steaming on all main engines during the refueling process, not to mention the incursion of port fees for inport refueling operations. In addition, needlessly refueling removes an asset from station for the time required for refueling. The periodic schedule wastes man hours and can add stress to a crew already dealing with high-tempo operations in today's naval environment.

The proposed DSS will use weather data in conjunction with dynamic and stored fueling points to facilitate optimal path network analysis based on actual conditions rather than an oversimplified PIM model. The evaluation will be used to identify optimal or near optimal tacks to follow. It will be a scalable solution able to manage fuel on an individual ship, a destroyer squadron, carrier strike group or at the numbered fleet level. The system will provide not only point-to-point optimal solutions, but also will allow the fueling plans to encompass all operations. It can be modified whenever operational factors dictate deviations. Operational boxes (OPBOX) will be included in the solution where different levels of operations can be selected to account for varying fuel usage during operations.

The goal of the system is to allow decision makers to plan more efficient and economic usage of the limited resource of fuel onboard Navy ships. The Naval Fuel Management System will be a DSS tool in which a fuel plan can be created, allowing ships more time on station, minimizing periodic scheduled refueling, and needless brief stops for fuel (BSF).

THIS PAGE INTENTIONALLY LEFT BLANK

LIST OF ACRONYMS AND ABBREVIATIONS

AOTSR	Automated Optimum Ship Track Route
AOR	Area of Operations
BSF	Brief Stops for Fuel
CO	Commanding Officer
COC	Chain of Command
CONUS	Continental United States
CSG	Carrier Strike Group
DESRON	Destroyer Squadron
DFM	Diesel Fuel Marine
DIVTACS	Divisional Tactics
DoD	Department of Defense
DSS	Decision Support System
DTG	Date Time Group
FNMOC	Fleet Numerical Meteorology and Oceanographic Center
FSMD	Fuel Schedule Management Database
GIG	Global Information Grid
GUI	Graphical User Interface
IT	Information Technology
NFMS	Naval Fuel Management System
PIM	Position of Intended Movement
RAS	Refueling at Sea
SNR	Signal-to-Noise Ratio
SOA	Service-Oriented Architecture
SOP	Standard Operating Procedure
VIRT	Valued Information at the Right Time

THIS PAGE INTENTIONALLY LEFT BLANK

I. INTRODUCTION

A. BACKGROUND

Today's ships are limited in time on station based upon how much fuel they burn at sea. Awards are given to units who use the least fuel or are fuel conservative in their operations. However, little is done to manage and plan for fuel usage during training exercises and operational deployments alike. Tracking fuel usage from antiquated systems or on paper has become the norm and has created a reactionary disposition to refueling operations. Rather than planning and optimizing refueling points, refueling is either scheduled on a periodic basis, or arrangements are made one to two weeks in advance, giving little notice to the ports or ships that provide fuel.

A system can be developed that accurately predicts fueling requirements for a specified period of time, over either an operational or training deployment, to determine an optimized fuel path. The result is more time on station, less costs associated with refueling, and perhaps fewer ships required to maintain 24/7 operations.

B. PROBLEM

Current practices to determine fueling points use paper calculations in the form of burn charts, and an oversimplified model, the Position of Intended Movement (PIM), as input variables. The PIM model is oversimplified because it takes into account only a ship's course and speed; there is no offset for winds, tides or currents affecting how the ship actually moves through the water. Fueling arrangements are made either on a periodic basis or, at most, one or two weeks before the intended refueling date. The periodic refueling schedule wastes fuel both in reaching the refueling points, and steaming on all main engines during the refueling process, not to mention the incursion of port fees for brief stops for fuel (BSF). In addition, needlessly refueling removes an asset from station for the time required for refueling. The periodic schedule wastes man hours and can add stress to a crew already dealing with high-tempo operations in today's naval environment.

The Naval Fuel Management System (NFMS) will address these problems by providing a Decision Support System (DSS) that integrates diverse data sources, generates and solves an optimization model, and provides various data visualization interfaces that can in principle be deployed on several different technology platforms. The NFMS will allow decision makers and stakeholders to develop a fueling plan prior to a ship leaving the pier. This will allow a model to be generated to optimize which refueling points to use. If the weather or the destination or operational route changes as the plan progresses, decision makers can dynamically rerun the optimization model with new input variables providing an updated optimum plan. Thus, the refueling plan process gains a significant degree of flexibility over the current static methodology.

The methodology of this thesis is to first define the requirements for the NFMS, outlining which systems are currently available and which need to be acquired. Next a basic design of the NFMS will be developed using information flows. A proof of concept will be used describing where the calculations are made and how the system will define an optimized route based on the amount fuel burned for the overall fuel plan. Finally, some mock-ups of screen shots will be included to demonstrate they type of intuitive map based GUI, which should be utilized for this type of application.

C. SCOPE OF THE THESIS

The scope of this thesis is limited to requirements gathering and a basic system design. Because other UNCLASS and SECRET working systems are required to implement even a prototype system, full implementation will not be possible. A working Microsoft Excel™ shortest path transportation network analysis linear program will be designed around a single ship scenario for a proof of concept as the decision support engine for the system. Use-cases and storyboards will be used to demonstrate the functionality of the proposed DSS.

D. ORGANIZATION

The remainder of this thesis is separated into six chapters. Chapter II will describe and define the requirements for the NFMS. Chapter III describes the design for NFMS including services, data structures, and information flows. Chapter IV demonstrates the shortest path transportation network analysis proof of concept and Chapter V describes the user interfaces. Chapter VI is the concluding chapter summarizing recommendations and future work.

THIS PAGE INTENTIONALLY LEFT BLANK

II. NFMS DESIGN REQUIREMENTS

A. DECISION PARAMETERS

When designing a decision support system, it is necessary to consider the decision parameters that constrain the decision-making process. These parameters can be fleshed out by addressing a few key questions.

1. Who Are the Decision Makers and Stakeholders?

One way of identifying the NFMS decision makers and stakeholders is to work from lower unit levels up the chain of command (COC) within the Navy.

At the unit or ship level, the Commanding Officer (CO) is the key decision maker onboard. The CO ultimately decides where the ship will refuel and how often. Stakeholders onboard also include the Fuels Officer and/or the Chief Engineer who track fuel percentages onboard and report to the CO. The Operations Officer schedules the fuel stops and is also a key stakeholder in the decision-making process of fuel planning.

At the Group level, whether it is a smaller Destroyer Squadron (DESRON), or a larger Carrier Strike Group (CSG), the key decision maker is the Commodore. He is supported by the Operations Officer in the N3 code, and the Supply Officer in the N7 code, to arrange for Group level fuel planning. A larger group would normally have a refueling asset, in the form of an oiler to assist in sustaining operations, rendering this decision-making environment even more complex.

At the Fleet or Combatant Command level, the key decision makers are the Fleet Commanders or Combatant Commanders. These decision makers are looking at a much larger abstraction of groups of ships and how they are moving and refueling in a specific area of operations (AOR). The Fleet and Combatant Commanders will have refueling assets and ports assigned to them, as well as several oilers.

2. What Are the Decisions That Need to Be Made?

The key decision that needs to be made in the refueling environment is as follows:

- When and where should my/each ship refuel for an optimal route—a route that uses the least amount of fuel, but still allows for making the scheduled fixed ports on time?

3. What is the Time Window that Decisions Have to be Made?

The Navy needs to submit estimates of how much fuel it expects to use in any given fiscal year. If deployments and training exercises can be scheduled two years out, the NFMS can be used to create these fuel consumption estimates for the Navy as a whole. However, assuming that weather patterns and deployment schedules will not change over a two-year period is entirely unrealistic. Therefore, once a deployment or exercise timeline is mapped out by the Operations Officer at the Fleet, Group, or Unit level, then the refueling locations will immediately come into question. Typically, this can be as early as six months but typically no later than three months from when the ship is scheduled to leave the pier.

Since the weather predictions can change every 12 hours, then the optimal route can potentially change every 12 hours as well. This would be too volatile a timeframe to commit to any sort of a refueling plan. Also, it typically takes 36–48 hours to schedule a port call, even for a brief stop for fuel (BSF). Therefore, the decision to change a refueling port must occur within 36 hours of going into that port.

4. What is the Cost or Assumed Risk of a Poor Decision?

The highest possible risk would be a Navy vessel running out of fuel and needing to be towed into port. The cost would not only be tangible in the form of extra services for the towing tugs, but also intangible in the form of damage to the reputation of the Navy as a whole within the international sailing community.

A more likely risk is the cost accrued in wasted time and fuel for needless refueling. The tradeoff, therefore, is between running out of fuel and incurring the expense of refueling needlessly. However, on 12 October 2000, the largest and unexpected cost of a poor refueling decision was realized when the USS Cole was attacked in the Port of Aden. The USS Cole underestimated its fuel consumption going through the Suez Canal and needed to refuel. An impromptu BSF was called for the Port of Aden, and the terrorists took the opportunity to attack. Now it is standard operating procedure (SOP) that a security team does a sweep and risk assessment of any overseas port prior to a ship entering. The need for a security team to sweep a pier prior to refueling adds to the cost each time a ship pulls in to refuel. Therefore, these should not be wasteful, periodic or unnecessary stops, but rather, well thought out and optimal decisions for a refueling plan.

NFMS does not inherently lower the risk involved with operating at lower than comfortable fuel percentages. However, it gives Commanders at all levels a tool to plan and make decisions. By tying weather as part of the model, NFMS mitigates the risk of using unreliable inaccurate estimating techniques such as the PIM model. Therefore, Commanders will be more likely to take on more risk by allowing fuel percentages to drop lower than they were comfortable before having a DSS such as NFMS. Currently, without a DSS, Commanders mitigate the risk of running out of fuel by periodically refueling, a wasteful, simplistic and inefficient solution. NFMS gives the Commanders an alternate way to mitigate the risk by planning ahead of time with an accurate, optimized model.

5. Where do Risks and Uncertainties Lie in the Decision Process?

Weather and actual-versus-predicted fuel consumption provide the biggest uncertainty in the fuel-planning decision process. Also, as noted in the assumptions, ships often do not travel in a straight line, just going directly from port A to port B. Ships may perform various operations, such as practicing high-speed drills and maneuvers, or conducting divisional tactics (DIVTACS) exercises, or they may need to “drive for wind” in flight operations. All of these different maneuvers add complexity and uncertainty to the fuel planning decision process.

Because the fuel planning process is so difficult, U.S. ships refuel too often and waste time and resources needlessly refueling. If the complexity can be reduced by using a DSS such as NFMS, then large amounts of resources can potentially be saved, with ships spending more time on station and less time refueling or traveling to refuel.

B. NETWORK REQUIREMENTS

1. Service-Oriented Architecture (SOA)

As the Navy and the Department of Defense (DoD) transition to a net-centric environment, several documents drive new system acquisitions from stove-piped standalone systems to a service-oriented architecture (SOA) approach. Legacy stove-piped systems cause information to be hoarded rather than shared, which effectively blocks the proposed functionality of a system like NFMS. It is equivalent to tracking refueling locations and available assets on Excel™ spreadsheets or in-house databases, a practice still too common today. This old methodology of using information technology (IT) is inefficient and makes duplication of effort nearly unavoidable. The Global Information Grid (GIG) Architectural Vision [1] circumvents the hoarding of information by mandating the use of SOA that emphasizes the sharing of information through services. The GIG provides the vehicle to reduce duplication of effort, providing the kind of Net-Centrality needed to solve the refueling problem above. SOA as a requirement increases the reusability of systems and applications, which in turn, frees budget resources for developing useful new information systems and applications. The DoD Defense Information Enterprise Architecture [2] subsequently formalizes what is needed to have a secure SOA to support the GIG Architectural Vision. These documents are cited in the Defense Acquisitions Guide (DAG) [3], which requires that any IT acquisition must adhere to this model.

2. Valued Information at the Right Time (VIRT)

VIRT is a philosophy of how to build communication flows in order to achieve the highest efficiency within the bandwidth made available for any information system. This can be a difficult task in today's networked environment where systems of systems are constantly communicating. These communications often contain superfluous information, resulting in a low signal-to-noise ratio (SNR). VIRT suggests that the most efficient way to share information is to first define an ontology, or standard framework of vocabulary for the application domain, and then identify the information of value, and when it is relevant to send [4]. An example of VIRT is a traffic stop light camera. It monitors an intersection on a 24/7 basis; however, no data is transmitted until a car runs a red light.

SOA and VIRT by their nature have conflicting objectives when it comes to bandwidth consumption. The end user of NFMS will be operating on ships, where the only source of connectivity is often through SHF satellite communications. This makes bandwidth a valuable and constrained resource. Any information sent across the satellite network should be valuable. The DoD requirement of a SOA approach to solving problems with IT can be seen as in direct conflict with operating in a constrained bandwidth environment. SOA can be noisy, requiring many function calls across networks to solve a problem. Valuable information is defined as being timely, relevant, and concise. By applying the principles of VIRT, the valuable information can be identified. A condition monitor can be used and the limited bandwidth can be utilized only when the condition monitor detects that information needs to be sent to the ship. VIRT is an ideal solution to the problem of using a SOA approach in a constrained bandwidth environment and is recommend as part of the NFMS solution.

C. MODELS

NFMS is essentially both a data-driven and model-driven DSS [5]. The models essentially drive the data requirements, so we will discuss them first.

1. Route Generator Model

The simplistic PIM model to predict fuel percentages is not robust enough to provide a level of confidence sufficient to predict fuel usage accurately and to serve as the basis for an optimal fuel plan. Therefore, a route generator model is needed that takes into account the currents, tides, and winds of the sea. If a ship hits heavy weather, then more fuel will be expended to go through the storm. Also, if the winds and seas are “following,” then the ship will use less fuel than predicted by the PIM model. Weather can be unpredictable and must be monitored constantly to ensure significant changes are applied to the route. Therefore the route generator should be able to provide a closer prediction to the actual courses and speeds needed to get to each fixed port on time, using weather as an offset to PIM course and speed.

2. Refueling Optimization Model

In operations research, a linear program can be used to solve a shortest path transportation network problem, identifying the shortest path for a vehicle to take within the transportation network. This well-known analysis is based upon weighted links. The transportation network model is at the heart of the NFMS, providing the necessary computational engine to identify the optimal route.

D. DATA

Since NFMS is both a model and data driven DSS, there are significant data integration requirements in order to instantiate, and ultimately solve, any particular model.

1. Fuel Schedule Management

The NFMS will need a fuel schedule management system that enumerates which days of the year oilers and ports are available for refueling. Port availability can be tracked simply by date time groups; oiler data, however, is multi-dimensional. An oiler can be available at different locations throughout the oceans at different times, and its schedule can change frequently. Therefore, a service is needed that makes the oiler schedule data available in a format NFMS can interpret.

The scope of this thesis is not to define the requirements for the supporting systems feeding the NFMS, but rather to identify the requirements and suggest a design for the NFMS itself. A Fuel Schedule Management system is one of the required supporting services needed for the NFMS.

2. Weather Data

Weather data needs to be available consistently to the NFMS and provide periodic updates of the weather along route of the fuel plan. Variations in the weather can cause cascading changes ultimately affecting the optimal fuel plan; therefore, an early rather than later realization of weather changes is a critical success factor for NFMS. Also, it is necessary to recall that a 36- to 48-hour notice is normally required to change rendezvous arrangements with oilers as well as port calls for refueling.

3. Transportation Network Generation Data

Once potential fueling points are identified by the fuel scheduling system and the weather is applied to routes, transportation network data can be created by the NFMS. This data includes the waypoints of a particular route. A waypoint may be a port, an oiler rendezvous or just a turn in the sea. Waypoints will be defined by date time groups and will also have the actual courses and speeds associated with them. If a beginning fuel percentage is known, then each waypoint may have an associated fuel percentage, ultimately predicting the use of fuel along the route.

E. USER INTERFACES

1. Input

Input to the NFMS should be mostly automated, straightforward text-based data. Latitude and longitude should be available to set waypoints as well as selecting port names and oilers for reuse of information throughout the system. Ports and Oilers should be set as fixed/hard unchangeable stops, or else they will be considered soft points that can be omitted or the times of refueling can change to reveal an optimal plan.

The user should be also be able to input daily updated fuel percentages to track if the ship is maintaining the optimal plan within sensitivity limits.

2. Visualization

NFMS should use a map based graphical user interface (GUI) to show the optimal route. Also, a summary report of speed changes and fuel percentages along the route should be made available to the user for self tracking.

NFMS will solve the complex problem of when to refuel Navy ships. This will allow Commanders to feel comfortable taking on more risk by going lower on the reserve stock of fuel onboard. The trade-off is a more efficient use of fuel and a cost savings to the Navy. Requirements to solve such a complex problem include services for weather and route generation, as well as models to ensure the most efficient path is taken, which still allows ships to make their port of call on time. Also, the interface should be straightforward and intuitive. Next will be an initial design that uses some existing services currently available for such an application and identifies other valuable systems the Navy should invest in to make NFMS DSS operational.

III. SERVICES, DATA STRUCTURES AND INFORMATION FLOW DESIGN

A. PROPOSED NETWORK TOPOLOGY DESIGN

By applying the philosophy of VIRT to SOA, it becomes obvious that most of the processing will need to take place on shore where bandwidth is more readily available, and the messages from ship to shore made as efficient as possible. The proposed network topology design for NFMS reflects this constraint, as shown in Figure 1. There are two major components to the NFMS: A ship component where the user will interface with the system, providing inputs and requesting and maintaining fuel plans, and a shore side component where the server will receive the variables, requests, and updates to the fuel plan, interact with the route generator and the Fuel Schedule Management Database (FSMD), and return an optimized fuel plan. A route generator service is currently available from Fleet Numerical Meteorology and Oceanographic Center (FNMOC), so FNMOC will need to be a node in the network topology. Additionally, NFMS requires a Fuel Schedule Management Database that will need to be developed as a service for the fleet. A node containing the FSMD server will also be part of the NFMS network topology. The NFMS CONUS server will also act as a condition monitor from the VIRT philosophy to alert the ship when the plan has changed, either due to weather changes (provided from FNMOC) or the availability of better refueling options (provided from the FSMD).

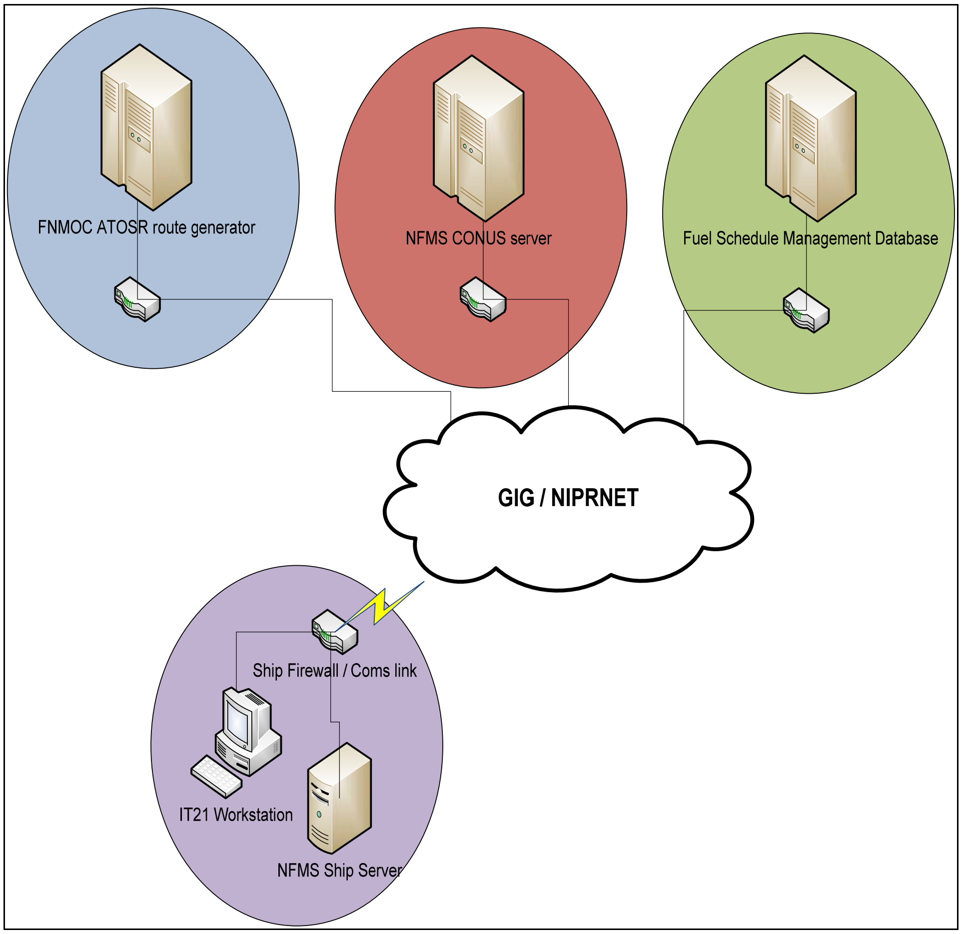

Figure 1. NFMS High Level Diagram

B. AUTOMATED OPTIMUM SHIP TRACK ROUTE

NFMS will use an existing IT application provided by FNMOC called Automated Optimum Ship Track Route (AOTSR) that will provide the route generator service [6]. Detailed descriptions of data input and output formats will be discussed later in this chapter. The AOTSR works over the Web using XML for its input and output interface. The service takes as input a series of waypoints with associated date time groups (DTGs), and returns an optimum track set of waypoints, based on weather predictions in that area. AOTSR uses historical climate data to produce its tracks for long term planning. For short term planning, AOTSR uses the current forecast available in the AOR. It returns actual course and speeds required to reach the waypoints on time. By using the AOTSR, the current oversimplified calculation determining the PIM track is replaced by estimated actual courses and speeds to get to each waypoint on time. This will provide a better estimate of fuel consumption, rendering NFMS a more reliable and accurate DSS in the process.

C. FUEL SCHEDULE MANAGEMENT DATABASE

NFMS will also require a database of current and future refueling points available as another service. Current refueling operations occur on either a periodic or ad-hoc basis, and are tracked manually. The only records of set refueling plans are naval messages sent between ships making arrangements. There is no set database to track current and future refueling operations. There are two ways Navy ships receive fuel: either by refueling at sea (RAS), or pulling into port for a brief stop for fuel (BSF). BSFs are often combined with liberty ports where ships stay for a longer period of time. A proposed FSMD will be recommended as part of NFMS. This database, in addition to providing a critical service required for NFMS, could also serve as a central repository for de-conflicting fueling operations throughout the Navy. It would be able to answer the following questions:

- Which ports are open for refueling and when?
- Will my ship's draft allow me to use this port for refueling?
- What are the RAS rendezvous on a particular day / time with a fleet oiler?
- What are the current positions and future movements of the fleet oilers?

Creating a database of refueling information would fit naturally into the SOA paradigm. This thesis sketches a few preliminary ideas for the structure and usage of an FSMD but leaves the full development of such a database to future research efforts.

D. TRIGGERS THAT CHANGE THE FUEL PLAN

Once an optimized plan is created and the ship is committed to it, the three CONUS servers will work to ensure the route remains optimum or near optimum. There are several conditions that would require the route to be altered. In each of these scenarios, changes of state in the fuel plan should automatically prompt the ship that its fuel plan has changed without the need for manual user input.

1. Since weather forecasts are published to AOTSR twice a day, a new weather pattern may alter the weights of the links sufficiently to require a change in route.

2. If a scheduled refueling point changes its state (e.g., a fleet oiler does not sail, or there is a port closure), then that node will be removed from the transportation network necessitating a change in the route.

3. If a new refueling point becomes available for possible scheduling, it may potentially provide a more efficient path to take.

For these three scenarios, a periodicity of 24 hours should be used to check the plan for optimal efficiency. This 24-hour cycle will take into account any new weather predictions and the updating of fueling points in the database. If the optimized plan remains unchanged then a “heartbeat” can be sent to the ship indicating no change. If the optimized path has changed, the new computed route should be sent.

There are several conditions which, if triggered from the ship side, could also result in changes to the optimum plan:

1. If the current fuel percentage does not match the planned fuel percentage, within sensitivity.

2. If the fixed/unchangeable waypoints for the ship change due to ship schedule changes.

3. If the endpoint changes due to ship schedule changes.

Each of these scenarios would require updated input variables to the NFMS, which could then recompute the optimization analysis on current weather and refueling points to return an optimal path.

In summary, the proposed network topology in Figure 1 describes three systems in CONUS working in synch to provide information to the ship connected wirelessly via satellite. The ship-shore satellite communications are where the VIRT principle needs to be assiduously applied. What the ship requires from the NFMS CONUS server is the current optimized fuel plan, as well as any triggers, or alerts that can potentially affect the current plan. What the CONUS server requires form the ship in order to calculate a fuel plan is ship location, expected fuel percentage at the start of the plan, destination location(s), fixed expected stops, and refueling activities at those stops, if any. After these variables are provided to the NFMS CONUS server, it can subsequently request the requisite large quantities of information from the AOTSR and the FSMD without compromising the limited ship-to-shore satellite bandwidth capacity.

E. INFORMATION FLOW DESIGN

Now that the high-level network topology for NFMS has been specified, and the change scenarios enumerated, the next step is to define the information flows amongst the systems, including the data schema required for each scenario. The following information flows are provided in detail to show how the services will interact to generate and maintain the optimal fuel plan.

The first information flow documents the most basic process, the initial plan creation. The initial solution of the optimization model becomes the baseline plan from which subsequent update operations are performed if and when necessary.

1. Initial Plan Creation

a. Input to CONUS

Generation of an initial plan will be initiated by an input from the ship side systems. A user will first select a new plan that the server will assign a unique identifier to ensure that the most current plan is always utilized. Since the planning inputs will be sent to the CONUS server, the plan identifier should be unique to each ship. The recommended numbering schema is SSSSSppppvv where

SSSSS	ship ID
pppp	plan #
vv	version # of the plan

Ex: *DDG69000101* refers to Ship *DDG69*, Plan *0001*, Version *01*.

The ship server will need some initial variable inputs from the user to begin the planning process. These will be provided as a series of waypoints. The waypoints will be predefined in the server as the most common stops that U.S. Naval vessels use, for example Norfolk, VA, San Diego, CA, Mayport FL, Everett, WA, and many overseas ports such as Bahrain, Dubai, Mallorca Spain, Rota, Malta, and Djibouti . The ports will also require associated date time groups (DTG). The initial beginning waypoint will only require a departing DTG whereas the ending waypoint (n) will only require an arrival DTG. All waypoints in between will require both an arrival and departure DTG. All DTG should be kept in Zulu, which will minimize the need to adjust for time zones and avoid any errors associated with such calculations. Each waypoint entered by the user for initial plan creation should be a hard, fixed stop since the intent is for NFMS to find the optimum refueling points along a fixed track. For example, if it is more fuel efficient to pull in for a three-day liberty port, then RAS the next day, the system will return that track.

The user will next enter the beginning fuel percentage for the voyage plan. The system should default to approx 90%, as most ships are not always at 100% when beginning a voyage. Finally, the user should enter the required refueling percentage for pulling into port on its final stop. The default should be set around 80%, as this is the most common requirement.

If the ports are known to the system, then there is no need to send the latitude and longitude as well. This would be sending extraneous, repetitive information in violation of the VIRT philosophy. Adding a new port to the system is a special use-case that will be defined in the use-case section. The database of known ports should be synchronized across all the ships and the CONUS server; therefore, only a unique identifier will need to be passed for each waypoint. The example input in Table 1 does not show the port name, all NFMS will have an updated repository of port names as shown in Table 2. This way only the port name identifier number will be transmitted, minimizing the size of each transition, and allowing for standardization of well-known and used ports.

A summary of input variables from the ship server to NFMS CONUS server for an initial fuel plan is as follows:

Type	ID	Waypoint #	Port ID	Arrive	Depart	Percentage Given/Required
1	DDG69000101	1	569	N/A Begin Plan	01-Jan-2011, 0830z	83%
1	DDG69000101	2	801	08-Jan-2011, 1000z	11-Jan-2011, 1200z	
1	DDG69000101	3	203	16-Jan-2011, 0900z	18-Jan-2011, 1200z	
1	DDG69000101	4	506	05-Feb-2011, 1215z	12-Feb-2011, 1300z	
1	DDG69000101	5	538	28-Feb-2011, 1500z	08-Mar-2011, 1000z	
1	DDG69000101	6	301	15-Mar-2011, 0800z	19-Mar-2011, 1045z	
1	DDG69000101	7	569	31-Mar-2011, 0800z	N/A End Plan	85%

Table 1. Summary of input from ship to NFMS CONUS server

The location of the port can be found by using the table of common ports, which should be located and updated on the NFMS CONUS server, and replicated on each ship server. Table 2 represents a small excerpt of the table for this example.

NFMS CONUS Server Table of Port Names and Locations			
ID	**Port Name**	**Latitude**	**Longitude**
569	Norfolk, VA	36°59’33”N	76°20’32”W
801	Rota Spain	36°34’59”N	6°20’35”W
203	Malta	35°48’48”N	14°25’51”E
506	Dubai	25°17’22”N	55°16’13”E
538	Mallorca Spain	39°19’45”N	2°55’14”E
301	Portsmouth England	50°47’20”N	1°06’36”W
569	Norfolk, VA	36°59’33”N	76°20’32”W

Table 2. Excerpt of NFMS CONUS Server table of port names and locations.

The NFMS will also need to know the different types of tables and message schemas available. Table 3 represents an excerpt of this table for this example.

NFMS Message Types	
Type ID	**Name**
1	Request New Plan
2	Return Fuel Points
3	Optimized Plan Result
4	Optimized Plan Update
5	Optimized Plan Replace
6	Current Fuel Percentage Update

Table 3. Excerpt of NFMS table of message and or table types.

b. Request Fuel Points

Once the NFMS CONUS server has the full set of required input variables, it can request, via a function call, fueling points along the voyage from the FSMD. The return data will be a series of potential refueling points a ship can use along its voyage plan. A limit to the distance from the initial track alternate points will be searched for can be defined as the mean speed of ship multiplied by the time it takes to reach exhaustion of fuel. This will be different for each ship class, and will yield a large, but limited, number of alternate refueling points along a track. In addition, when a fleet oiler is a potential stop, the optimal RAS rendezvous location will be revealed in the analysis as well. Data returned from the FSMD to the NFMS CONUS server should be either the port location along with the DTG for arrival and departure for a BSF, or the oiler ID, RAS rendezvous latitude and longitude and DTG.

Message Type	Plan ID	Point #	Point Type	Ship ID	Port ID	Latitude	Longitude	DTG
2	DDG69000101	1	Port	N/A	203	N/A	N/A	16-Feb-2011, 0730z
2	DDG69000101	2	RAS	TAKE1	N/A	36°34'59"N	6°20'35"W	19-Feb-2011, 0930z
2	DDG69000101	3	Port	N/A	506	N/A	N/A	23-Feb-2011, 1900z
2	DDG69000101	4	RAS		N/A	50°47'20"N	1°06'36"W	23-Feb-2011, 1900z
2	DDG69000101	5	Port	TAOE6	506	N/A	N/A	4-Mar-2001, 1600z
2	DDG69000101	.	.	.	.	.	.	.
2	DDG69000101	.	.	.	.	.	.	.
2	DDG69000101	.	.	.	.	.	.	.

Table 4. Summary table of potential refueling points from the FSMD to the NFMS CONUS server.

c. Build Transportation Network

At this point, the NFMS CONUS server has the data it needs to begin the transportation network analysis to find the optimal path. Every combination of refueling waypoints and fixed voyage plan waypoints will be paired as individual links in the overall plan. Each pairing will be sent to the FNMOC AOTSR route generator service to obtain the predicted courses and speeds, which can then be used to calculate the weight of the links in the transportation analysis. The FNMOC AOTSR is a production system with established input and output schemas.

Figure 2 is an example of the input required for the FNMOC ATOSR route generator Web service. The original example had 10 waypoints. Figure 2 has points 3–10 removed to demonstrate how the Web service can be used to obtain the course and speed between two points. Note, the ship's class is input to the Web service, since the model the service uses to predict course and speed includes draft and sail area of a particular ship class. This is because winds and currents affect each ship class differently. This means that the return predicted course and speeds will be more accurate than the standard PIM model used today to calculate future burn rates. The Web service also takes input and output in an XML format. Since XML is already used to define the interface for the route generator Web service, in order to maintain interoperability, NFMS CONUS server, NFMS ship server, and the FSMD should also use XML as the baseline ontology and passing information between services. A route generation request will be sent for each pair of waypoints in the transportation network built by the FNMOC CONUS server.

```
<RouteGenRequest>
<RequestId>MOVREP260_200801072354</RequestId>
<Classification>
<Level>UNCLASSIFIED</Level>
<Caveat>FOUO</Caveat>
<Derivation>Derived From: </Derivation>
<Declass>None</Declass>
</Classification>
<RequestType>WEAX</RequestType>
<Description>AOTSR Request to Generate Route for MOVREP id:260</Description>
<Passage>PORT:  USA,WA,Seattle  (47-36N,122-20W)  to  PORT:  USA,CA,San  Diego  (32-
43N,117-11W)</Passage>
<Units>english</Units>
<ShipInfo>
<Ship>RAINIER</Ship>
<Class>UNK 0</Class>
<ForeDraft>14.0</ForeDraft>
<AftDraft>14.0</AftDraft>
<MaxHeadSea>12.0</MaxHeadSea>
<MaxBeamSea>12.0</MaxBeamSea>
<MaxFollowSea>12.0</MaxFollowSea>
<MaxTrueWind>35.0</MaxTrueWind>
<MaxRelWind>35.0</MaxRelWind>
<MaxSpeed>12.0</MaxSpeed>
</ShipInfo>
<DepDTG>200801072346</DepDTG>
<ArrDTG>200801151946</ArrDTG>
<Models>
<WindModel>NOGAPS</WindModel>
<WaveModel>WW3_GLOBAL</WaveModel>
<CurrentModel>TOPS_GLOBAL</CurrentModel>
</Models>
<Points>
<Point>
<PointId>1</PointId>
<WpNumber>1210</WpNumber>
<Latitude>47.6</Latitude>
<Longitude>-122.33333333333333</Longitude>
<DTG>200801072346</DTG>
</Point>
<PointId>2</PointId>
<WpNumber>1211</WpNumber>
<Latitude>48.4</Latitude>
<Longitude>-122.9</Longitude>
<DTG>200801080746</DTG>
</Point>
</Points>
</RouteGenRequest>
```


Figure 2. XML schema from NFMS CONUS server to FNMOC Route Generator Web Service. From [6].

Once the AOTSR route generator has generated the route for each pairing of waypoints the information returned will be as shown in Figures 3–5. This sample output was provided by FNMOC Monterey with Waypoints 3–10. The AOTSR route generator service can accept more than two points, and may return more than two points for each pairing of waypoints. The sample output is broken down into header information and point information.


```
<RouteGetResponse>
   <ResponseStatus><Success/></ResponseStatus>
   <Classification>
     <Level>UNCLASSIFIED</Level>
     <Caveat>FOUO</Caveat>
     <Derivation>Derived From:</Derivation>
     <Declass>None</Declass>
   </Classification>
   <Header>
     <RequestId>MOVREP260_200801072354</RequestId>
     <RequestType>WEAX</RequestType>
    <Description>AOTSR Request to Generate Route for MOVREP id:260</Description>
    <Passage>PORT: USA,WA,Seattle (47-36N,122-20W) to PORT: USA,CA,San Diego (32-43N,117-
11
     <Units>english</Units>
     <CreationDate>02/05/2008</CreationDate>
     <CreationTime>00:04:38</CreationTime>
     <Ship>RAINIER</Ship>
     <DepartureDate>01/08/2008</DepartureDate>
     <DepartureTime>00:45:00</DepartureTime>
     <TimeEnroute>187.75</TimeEnroute>
     <DistanceEnroute>1339.24</DistanceEnroute>
     <PowerEnroute>136.38</PowerEnroute>
     <RequiredSpeed>7.1</RequiredSpeed>
      <Models>
        <WindModel>NOGAPS</WindModel>
        <WaveModel>WW3_GLOBAL</WaveModel>
        <CurrentModel>TOPS_GLOBAL</CurrentModel>
      </Models>
   </Header>
```


Figure 3. Sample output from FNMOC Route Generator Web Service (header). From [6].

```xml
<PointsList>
   <Point>
    <PointId>1</PointId>
    <WpNumber>1210</WpNumber>
    <DTG>200801080045</DTG>
    <Latitude>47.600</Latitude>
    <Longitude>-122.333</Longitude>
    <NavType>GC</NavType>
    <ShipSpeed>6.60</ShipSpeed>
    <ShipCourse>334.85</ShipCourse>
    <WindSpeed>14.60</WindSpeed>
    <WindDirection>343.77</WindDirection>
    <SigWaveHeight>0.00</SigWaveHeight>
    <SeaHeight>0.00</SeaHeight>
    <SeaPeriod>0.00</SeaPeriod>
    <SeaDirection>0.00</SeaDirection>
    <SwellHeight>0.00</SwellHeight>
    <SwellPeriod>0.00</SwellPeriod>
    <SwellDirection>0.00</SwellDirection>
    <CurrentSpeed>0.00</CurrentSpeed>
    <CurrentDirection>0.00</CurrentDirection>
    <EnvironLimits>
      <MinDist35></MinDist35>
      <MinDist50></MinDist50>
      <RelWind>0</RelWind>
      <SwlHtBeam>0</SwlHtBeam>
      <SwlHtFollow>0</SwlHtFollow>
      <SwlHtHead>0</SwlHtHead>
      <TrueWind>0</TrueWind>
      <WvHtBeam>0</WvHtBeam>
      <WvHtFollow>0</WvHtFollow>
      <WvHtHead>0</WvHtHead>
      <DepthWrngs>Land</DepthWrngs>
    </EnvironLimits>
    <HorsePower>1.33</HorsePower>
    <Distance>34.54</Distance>
    <WindSource>Climatology</WindSource>
    <WaveSource>Climatology</WaveSource>
    <CurrentSource>TOPS_GLOBAL-2008020400</CurrentSource>
    </Point>
```


Figure 4. Sample output from FNMOC Route Generator Web Service (point1). From [6].

```xml
    <Point>
    <PointId>2</PointId>
    <WpNumber></WpNumber>
    <DTG>200801080600</DTG>
    <Latitude>48.121</Latitude>
    <Longitude>-122.700</Longitude>
    <NavType>GC</NavType>
    <ShipSpeed>6.60</ShipSpeed>
    <ShipCourse>334.58</ShipCourse>
    <WindSpeed>14.48</WindSpeed>
    <WindDirection>351.77</WindDirection>
    <SigWaveHeight>0.00</SigWaveHeight>
    <SeaHeight>0.00</SeaHeight>
    <SeaPeriod>0.00</SeaPeriod>
    <SeaDirection>0.00</SeaDirection>
    <SwellHeight>0.00</SwellHeight>
    <SwellPeriod>0.00</SwellPeriod>
    <SwellDirection>0.00</SwellDirection>
    <CurrentSpeed>0.00</CurrentSpeed>
    <CurrentDirection>0.00</CurrentDirection>
    <EnvironLimits>
      <MinDist35></MinDist35>
      <MinDist50></MinDist50>
      <RelWind>0</RelWind>
      <SwlHtBeam>0</SwlHtBeam>
      <SwlHtFollow>0</SwlHtFollow>
      <SwlHtHead>0</SwlHtHead>
      <TrueWind>0</TrueWind>
      <WvHtBeam>0</WvHtBeam>
      <WvHtFollow>0</WvHtFollow>
      <WvHtHead>0</WvHtHead>
      <DepthWrngs></DepthWrngs>
    </EnvironLimits>
    <HorsePower>0.71</HorsePower>
    <Distance>18.58</Distance>
    <WindSource>Climatology</WindSource>
    <WaveSource>Climatology</WaveSource>
    <CurrentSource>TOPS_GLOBAL-2008020400</CurrentSource>
    </Point>
   </PointsList>
</RouteGetResponse>
```

Figure 5. Sample output from FNMOC Route Generator Web Service (point2). From [6].

The route generator Web service provides significantly more information than is needed for the NFMS to find an optimum track. This is another reason underlying the proposed physical architecture. Since a large number of these relatively small messages will be required in order to obtain all the weights for the links in the transportation network analysis, rather than filling up the limited bandwidth from shore to ships resource, we locate a central server in CONUS where bandwidth is virtually unlimited and these information flows can be absorbed with relatively little impact upon the CONUS infrastructure. The NFMS CONUS server serves two functions. First, it is an intermediate processor handling all the function calls to the other CONUS based servers, building the plan and sending only the information needed by the ships, the optimized plan. Second, NFMS will act as a condition monitor, which continuously monitors the current optimal plan and only sends data to the ships if the state of the plan changes.

The only information the NFMS CONUS server needs to obtain the link weights are the speeds at each of the points for each of the pairings of waypoints and their associated distance. The transportation network route generator must pre-process and sum the gallons burned along each point to obtain the weights for each link. The preprocessing section of Chapter IV will go into detail on how this conversion takes place.

Once the transportation network is built, the optimal path discovery method described in Chapter IV will be executed. The optimal path will then be returned to the ship server, using the same ID for the initial fuel plan. This optimal plan should include estimated fuel percentages at each stop. An example of this data is as follows:

Message Type	Plan ID	Point #	Point Type	Ship ID	Port ID	Latitude	Longitude	Arrive	Depart	Arrive Fuel %	Depart Fuel %
3	DDG69 000101	1	Port	N/A	569	N/A	N/A	N/A	01-Jan-2011, 0830z	N/A	83%
3	DDG69 000101	2	Port	N/A	801	N/A	N/A	08-Jan-2011, 1000z	11-Jan-2011, 1200z	53%	98%
3	DDG69 000101	3	Port	N/A	203	N/A	N/A	16-Jan-2011, 0900z	18-Jan-2011, 1200z	83%	83%
3	DDG69 000101	4	RAS	1	N/A	50°47’20”N	1°06’36”W	21-Jan-2011, 0200z	21-Jan-2011, 0500z	46%	98%
3	DDG69 000101	5	Port	N/A	506	N/A	N/A	5-Feb-2011, 1215z	12-Feb-2011, 1300z	57%	98%
3	DDG69 000101	6	RAS	2	N/A	50°47’20”N	1°06’36”W	15-Feb-2011, 1200z	15-Feb-2011, 1500zz	55%	98%
3	DDG69 000101	7	Port	N/A	538	N/A	N/A	28-Feb-2011, 1500z	08-Mar-2011, 1000z	80%	75%
3	DDG69 000101	8	Port	N/A	301	N/A	N/A	15-Mar-2011, 0800z	19-Mar-2011, 1045z	50%	98%
3	DDG69 000101	9	RAS	3	N/A	50°47’20”N	1°06’36”W	28-Mar-2011, 1500z	28-Mar-2011, 1800z	20%	98%
3	DDG69 000101	10	Port	N/A	569	N/A	N/A	31-Mar-2011, 0800z	N/A	90%	N/A

Table 5. Summary table of optimized plan from NFMS CONUS server to ship.

This table will be transmitted in the form of an XML message and will be displayed by the ship server into a map-based GUI that the user will be better able to understand than reading text. Also, different reports will be available to the user to determine whether the ship is on or off the optimum voyage fuel plan. GUI interfaces and reports are described in Chapter V.

Figure 6 shows the information flows for initial plan creation in the “swimming lane” framework commonly used in information systems requirements analysis.

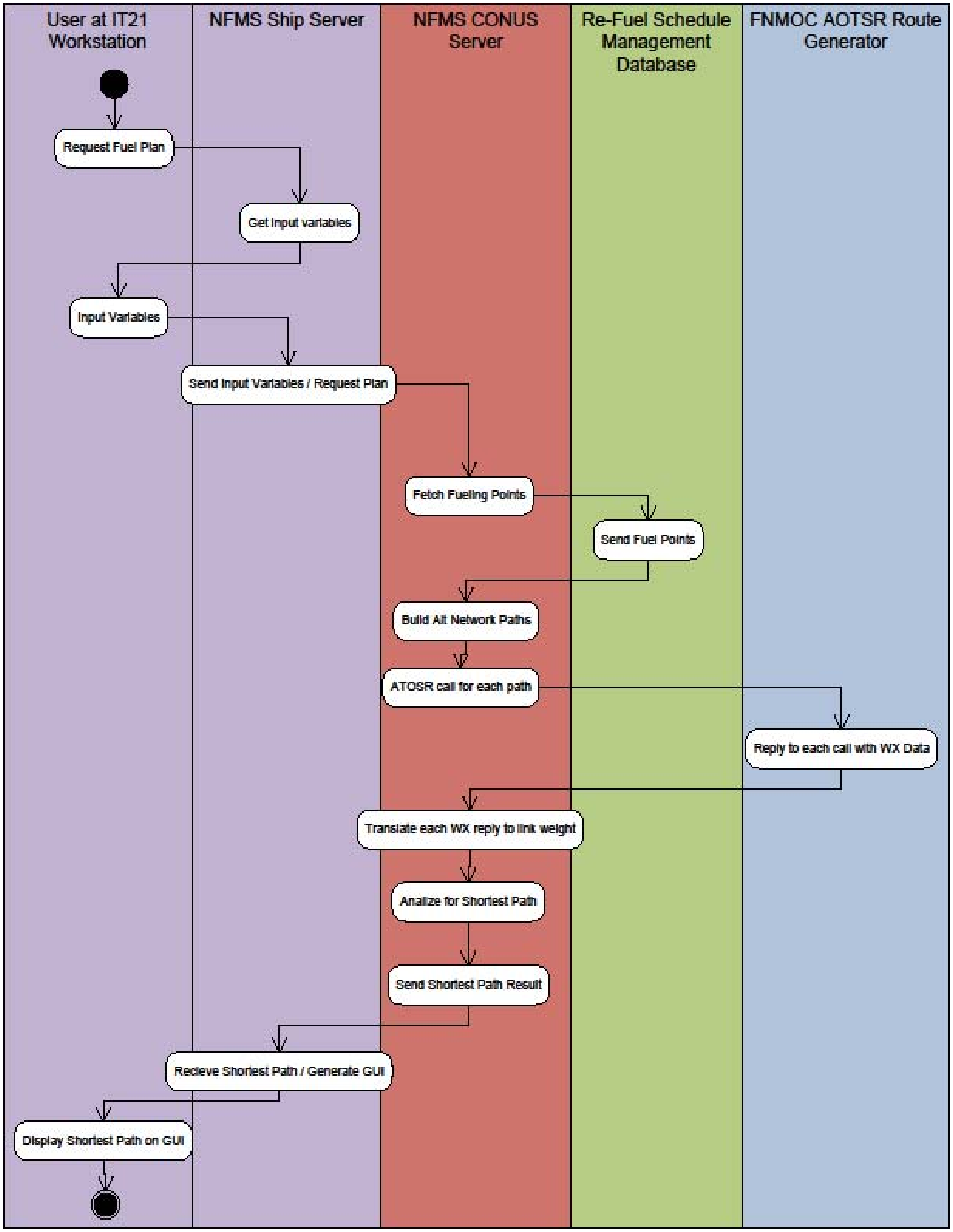

Figure 6. NFMS information flow for initial plan.

2. Periodic Fuel Plan Check Initiated at CONUS Server

a. Initial Conditions

Once the initial plan is created, it will need to be updated periodically by the CONUS server. Having the plan check initiated at the CONUS server provides three benefits:

1) It minimizes the amount of traffic being sent from the ship to the CONUS server.

2) Ships routinely operate at EMCON (emissions control), which is a state where all electronic communication is shut off to minimize emissions that can be used for tracking the ship's movements. Therefore, when the ship is up and available to receive information, the new plan will be waiting to be "pushed" to the ship.

3) Since the ship receives the new plan without having to initiate a connection, it also minimizes the amount of time the ship has to wait for the new plan.

Weather can change on an hourly basis; however, it would not be practical to update the plan on an hourly basis or even on an every-12-hour basis as forecasts are updated. If a storm develops unexpectedly, the ship must deal with avoiding the storm first, and then initiate a check of the plan after the storm has been avoided. Also, it is not feasible to change ports or develop RAS on the fly, with less than 36–48 hours' notice. This is one of the main reasons to have a planning system such as NFMS. It eliminates the need for last-minute changes while optimizing the voyage for overall fuel conservation. Therefore, a 24-hour cycle is recommended for the CONUS server to initiate a check of the plan. Also, the first 48 hours of the plan should be locked in, without the ability to be changed in order to avoid last-minute changes to the plan. The only exception to this should be if a planned stop changes in the FSMD, or the shipboard user purposefully changes a fixed waypoint.

b. Steps for 24-Hour Cyclical Fuel Plan Check

The following steps will take place in fuel plan monitoring mode:

1. While the plan is being executed, the CONUS server will initiate a check of the plan every 24 hours.

2. The CONUS server will send the remainder of the fixed plan, less the generated optimal fuel stops, to the FSMD. The format for this is described in Section 1 b of this chapter.

3. The FSMD will respond using the format described in Section 1 b of this chapter.

4. The CONUS server will then send all pairings as described in Section 1 c of this chapter to the FNMOC ATOSR Route Generator.

5. The CONUS server will then calculate all the links for the analysis and optimization model that is described in Chapter IV.

6. The CONUS server will then determine any differences between the old plan and the new plan, by looking first whether any points have changed, and second, whether any amount of fuel burned has changed between points. If the old plan is nearly identical to the new plan with only minor fuel percentage changes, the message sent to the ship server need only be a small subset of the overall new plan. An example follows:

Message Type	Plan ID	Point #	Change/No-Change	Point Type	Ship ID	Port ID	Latitude	Longitude	Arrive	Depart	Arrive Fuel %	Depart Fuel %
4	DDG69000102	1	No-Change									
4	DDG69000102	2	No-Change									
4	DDG69000102	3	Change								80%	80%
4	DDG69000102	4	Change								52%	98%
4	DDG69000102	5	No-Change									
4	DDG69000102	6	Change								60%	98%
4	DDG69000102	7	No-Change									
4	DDG69000102	8	No-Change									
4	DDG69000102	9	No-Change									
4	DDG69000102	10	No-Change									

Table 6. Summary table of NFMS CONUS Server fuel plan update to ship.

In Table 6, it can be seen that only the changed information is populated in the table, because this table will be the basis from which the XML message will be formed to pass from the NFMS CONUS server to the receiving ship. If the actual locations or dates of the plan had changed, then those fields would be filed with the updated information. The sequence number DDG69000101 now changes to DDG69000102 because the predetermined fuel percentages changed, which results in a new current plan on the CONUS sever. This ID methodology keep the plans organized and allows only the most recent plan in execution to be tracked every 24 hours for weather pattern prediction updates. This also provides a nomenclature for historical archiving of data for future data mining and tracking the evolution of fuel planning. If the waypoints change more than a few percentage differences, a full new optimal plan, as outlined in Section 1 c of this chapter, would need to be sent. The header information in the XML message passed would indicate type 5 for fuel plan replace with an ID of

DDG69000201 in the same format as Table 5. This would let the ship know that his new plan replaces all previous versions of DDG690001XX.

Figure 7 visually describes the information flows outlined above for the 24-hour cyclical fuel plan check by the CONUS server.

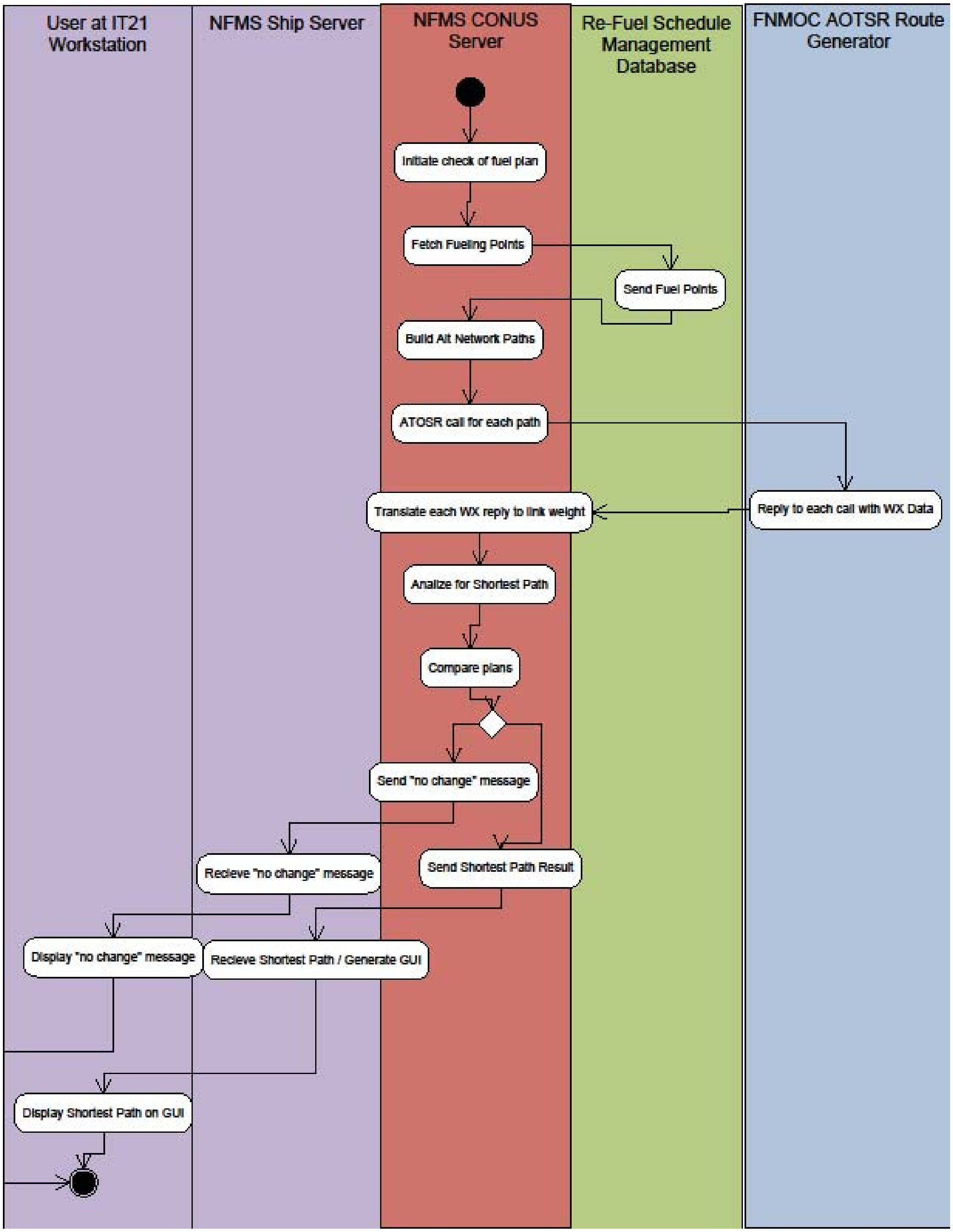

Figure 7. NFMS information flow check plan initiated by NFMS CONUS Server.

3. Verify Fuel Plan with New Input Variables

a. Initial Conditions

In addition to weather changes, ships can vector off course, or not follow the exact track predetermined by the NFMS. Also, the ports of call can change in the middle of a voyage. Therefore, updated input variables will be needed to be sent from the ship to the NFMS CONUS server from time to time to ensure the ship is on plan. Unlike the weather that can be updated on a periodic basis, i.e., every 24 hours, the variables from the ship are nonperiodic. However, updated fuel percentages taken from the ships tanks are required on a 24-hour basis by operational reporting requirements for all fleets when ships are deployed. Therefore, the updated fuel percentages should be input into the NFMS via the ship workstation by the user every 24 hours.

If the fuel percentages are within the sensitivity limits of the optimized voyage fuel plan, provided the sensitivity analysis data is on the ship server, the ship's server will not send any information to the CONUS server. In this case, the CONUS server will not be waiting for updates every 24 hours from the ship. If no updates are received, then the ship is on plan within limits and no further action is required. However, if the ship is off plan, and over the sensitivity limits provided by the analysis, then an update plan request will need to be initiated by the ship's server. In this situation, the only parameter changing is the initial fuel percentage of the plan. The CONUS server knows from the initial plan what the fixed waypoints are for the voyage and what the original planned route entails. The following is an example of an input variable change:

Message Type	**Plan ID**	**DTG**	**Latitude**	**Longitude**	**Fuel %**
6	DDG69000102	15-JAN-2011, 1200z	50°47'20"N	1°06'36"W	75%

Table 7. Summary table of input variable change from ship to NFMS CONUS server.

Once the request is received by the CONUS server, it will perform the following steps:

1. The CONUS server sends a new request to discover the potential fuel points based on the new input variable concatenated with the remainder of the fixed track to the FSMD. The format for this is described in Section 1 b of this chapter.

2. The FSMD will respond in the format described in Section 1 b of this chapter.

3. The CONUS server will then send all pairings as described in Section 1 c of this chapter to the FNMOC AOTSR Route Generator.

4. The CONUS server will then calculate all the links for the analysis and optimization model as described in Chapter IV.

5. The CONUS server will compare the old plan and the new plan. If the old plan maintains the same waypoints as the new plan with only minor fuel percentage changes, the message sent to the ship server is described in Section 3 a of this chapter.

b. Voyage Plan Fixed Waypoint Change

If the voyage plan changes entirely, e.g., if the ship is no longer going to Dubai, or Mallorca, but instead reroutes to Bahrain and Rota, a new plan will need to be generated. This will follow the same basic structure as described in this chapter with the following exceptions.

The type of message would be a plan replace. The old ID number DDG69000102 would need to be changed to a new plan ID and would be described as DDG69000201. After the plan ID number changes, the CONUS server will place the old plan in archives and will no longer be updating it on a 24-hours basis for weather pattern predication updates.

Figure 8 displays the information flows outlined above for the input variable changes by the NFMS ship server.

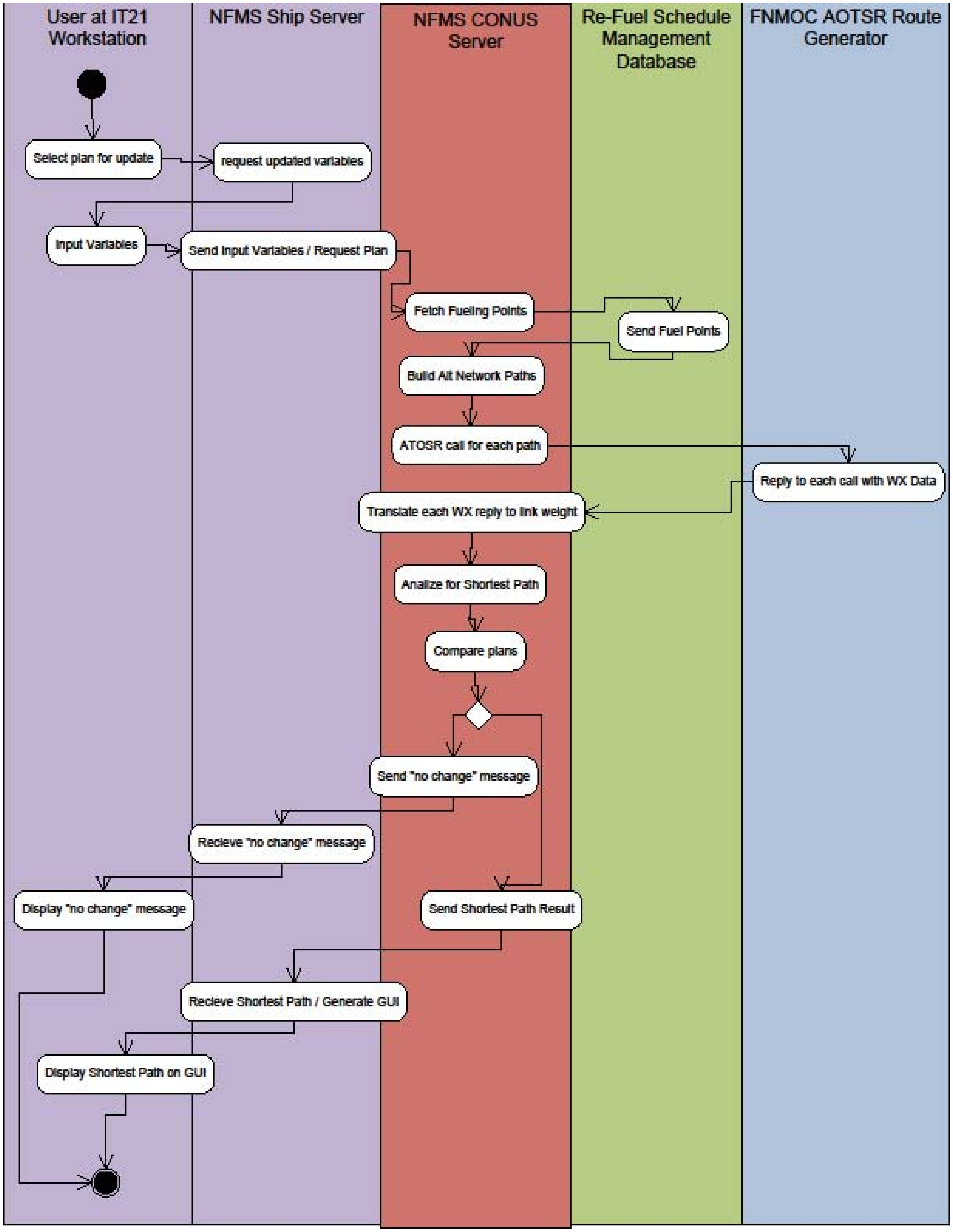

Figure 8. NFMS information flow update variables from ship.

In this chapter, we have specified the basic network topology and physical layout for the NFMS, taking into account the requirements for implementation as an SOA. The information flows we have developed leverage VIRT principles in trying to minimize bandwidth consumption from ship to shore. The next chapter provides a proof of concept using Microsoft Excel as an optimization engine to obtain an optimal solution that will be transmitted to the ship server.

IV. TRANSPORTATION MODEL AND ANALYSIS

We have now described the information flows, and required network infrastructure to design the NFMS. NFMS needs to interface with the FNMOC AOTSR to tie weather into the system providing a better model than PIM. NFMS needs to interface with FSMD to discover alternate paths. Both FNMOC AOTSR and FSMD also gives NFMS awareness to changes in the environment when NFMS asks for updated information. At its core, the NFMS is solving the problem of the optimal path in this case the optimal path is defined as the most fuel efficient path that still gets the ship to its required ports on time. First, NFMS needs to convert the data given from AOTSR into the relevant values to define the link weights for the optimal path.

Figure 9 is a graphical representation of a notional transportation network. In this notional example, the user has input three waypoints that are fixed/hard and will not change. On the graphic, these fixed points are noted by circles. The diamonds represent the potential refueling locations returned by the FSMD. The squares represent the waypoints returned by the FNMOC AOTSR, when a pairing of circles / circles, circles / diamonds and diamonds / diamonds are sent to the FNMOC AOTSR route generator. These waypoints are not set as a fixed number as the AOTSR route generator can return any number of waypoints between the paring given as seen in Figures 3–5. As described in Chapter III, the NFMS CONUS server would have sent these pairings of user and FSMD waypoints to obtain the course and speed due to weather data from FNMOC AOTSR. At first, NFMS will not know which potential links to filter based on DTG, speed of vessel, and percent of fuel to maintain. Therefore, all possible combination of pairing will need to be passed to the AOTSR route generator. Then a filter will be applied removing all unattainable links. Unattainable links are ones where the ship will run out of fuel, go below the required fuel percentage to maintain, and cannot make the associated follow-on nodes based on maximum ship speed. After all unattainable links are removed; a transportation network can be built based on associated DTGs with each node. In this nominal case where, NFMS has already filtered and built a transportation network with the following ordered pairs: (1,2) (1,3) (1,4) (2,5) (2,3) (3,4) (3,5) (4,5)

(5,6) (5,7) (5,9) (6,7) (6,9) (7,9) (7,8) and (8,9). These represent 16 different calls to the AOTSR, each of which can return any number of intermediate waypoints, since the AOTSR route generator defines a waypoint as a turn or change in speed due to weather or land avoidance. Links need to be built between the intermediate waypoints, and assigned weights. These weighted links will be summed to arrive at a single link weight across Lij.

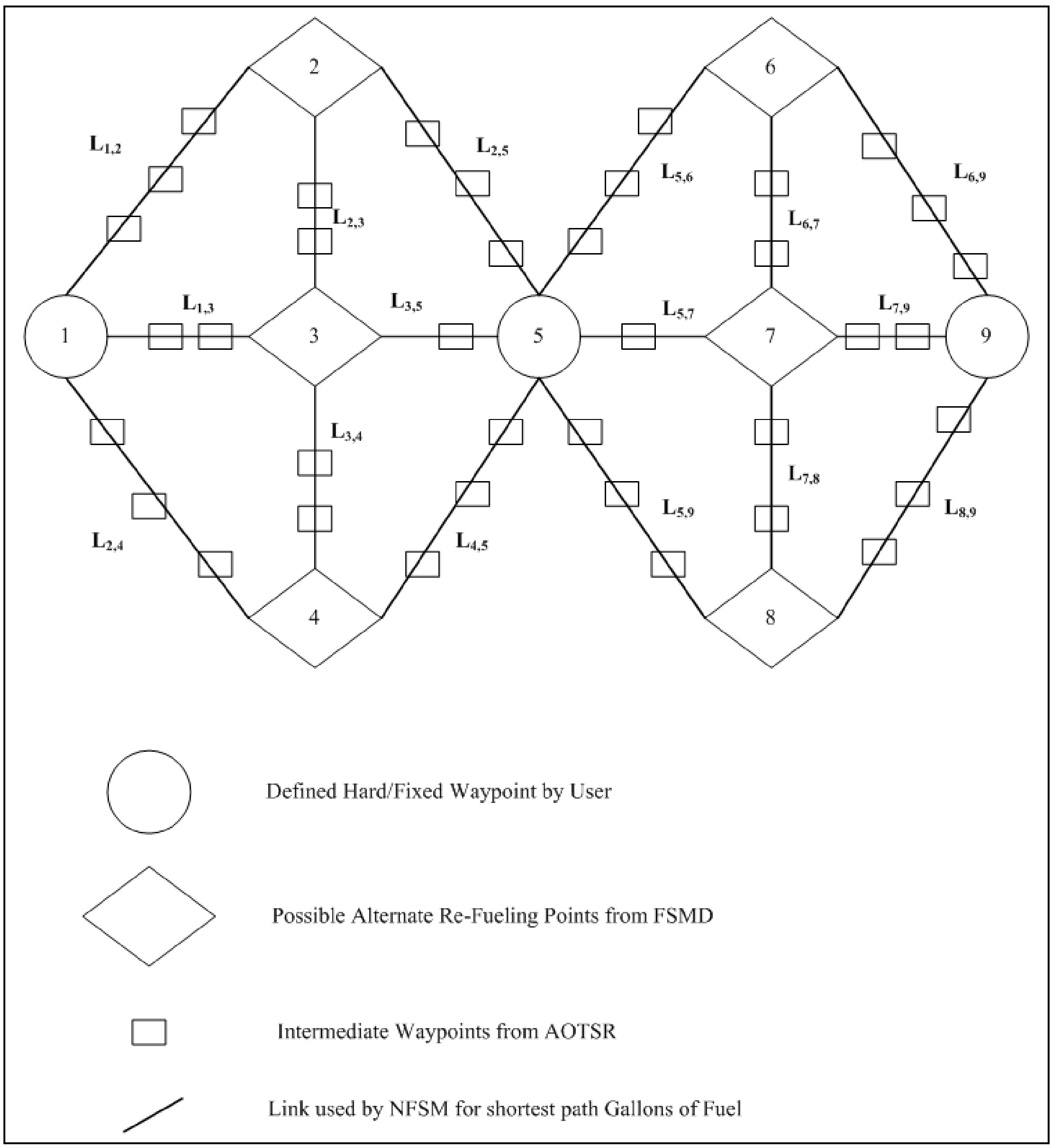

Figure 9. Notional graphical representation of transportation network.

A. MODEL PREPROCESSING REQUIREMENTS

The data collected from the AOTSR route generator is in the form of speed in knots between waypoints. These intermediate waypoints can each have differing speeds to reach them on time; these different waypoints are noted as W_k. Therefore, the NFMS CONUS server needs to have a database of fuel burn curves. These fuel consumption charts differ based on ship class, i.e., DDG, CG, FFG, LPD, LPD-17, LHD, LHA, or LHD. The curves define specific fuel burn amounts in gallons per hour based on ships ordered speed in knots and plant configuration. These types of curves can be seen in the NAVSEA Incentivized Energy Conservation Program Web site in both data only and graphed from [7]. Figure 10 and Table 8 are examples of reference data obtained on a DDG 51 class vessel.

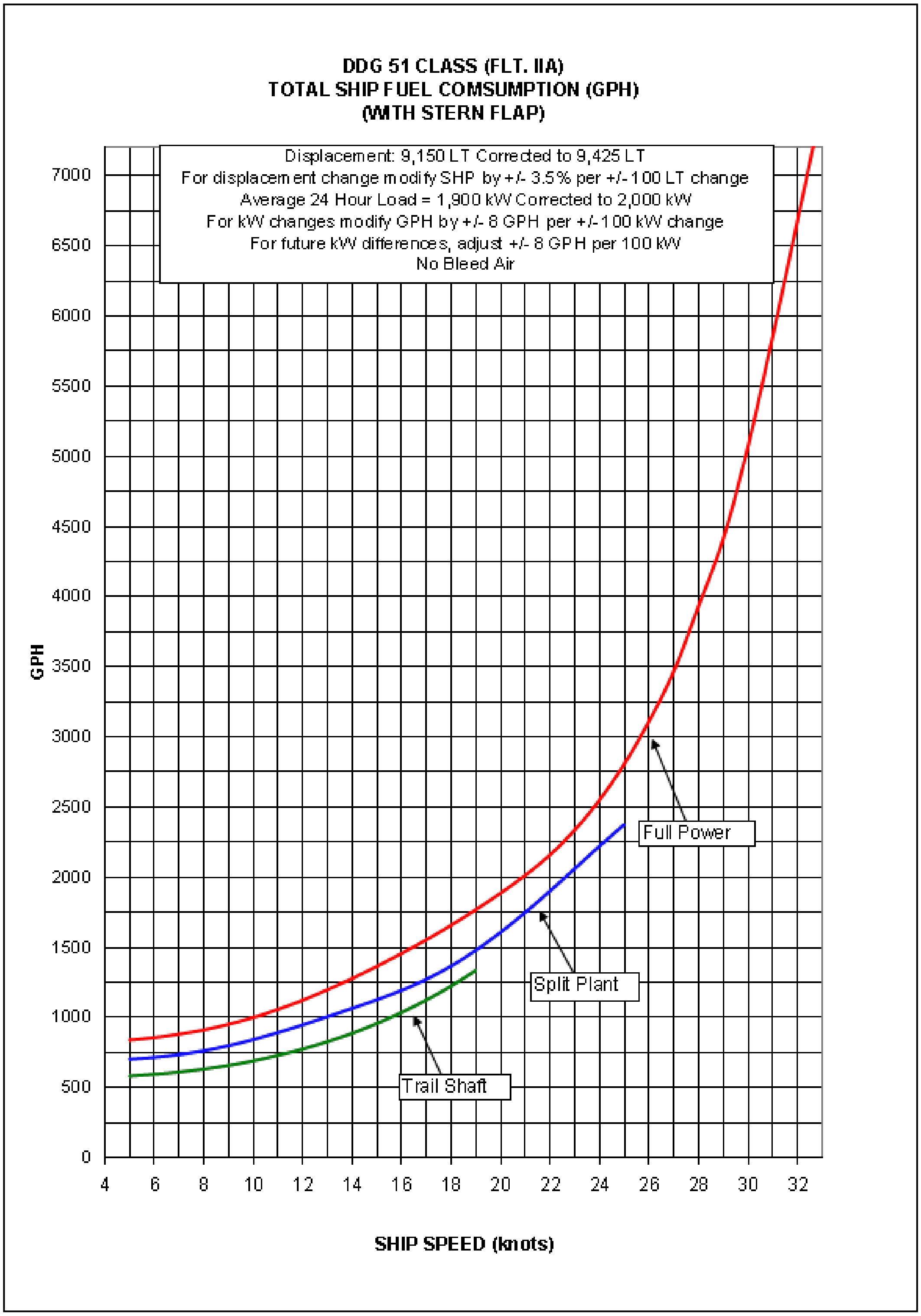

Figure 10. Fuel Curve of DDG 51 Class (FLT. IIA) Total Ship Fuel Consumption (GPH) (with Stern Flap). From [7].

DDG 51 CLASS (FLT. IIA) TOTAL SHIP FUEL CONSUMPTION

(With Stern Flap)

Source: Final Report USS Oscar Austin (DDG 79) Performance and Special Trials Results SEPTEMBER 2001
Displacement = 9,150 LT
For displacement changes modify SHP by +/- 3.5% per +/- 100 LT change
Average 24-Hour Load = 1,900 kW (324 GPH) from NAVSEA SECAT report aboard USS McFAUL (DDG 74)
For kW changes modify GPH by +/- 8 GPH per +/- 100 kW change
No Bleed Air
GPH = Gallons per hour; GPNM = Gallons per nautical mile
Trail shaft data is applicable to 100% and 80% propeller pitch

	TRAIL SHAFT			SPLIT PLANT			FULL POWER	
SHIP SPEED (KNOTS)	RPM	GPH	GPNM	RPM	GPH	GPNM	GPH	GPNM
5	31	581	116	31	701	140	837	167
6	32	593	99	32	714	119	854	142
7	37	609	87	37	733	105	879	126
8	42	630	79	42	761	95	910	114
9	47	656	73	47	797	89	950	106
10	52	689	69	52	840	84	998	100
11	58	728	66	58	890	81	1056	96
12	63	773	64	63	945	79	1121	94
13	68	825	64	68	1004	77	1196	92
14	73	886	63	73	1063	76	1276	91
15	79	955	64	79	1125	75	1363	91
16	84	1034	65	84	1192	75	1455	91
17	89	1123	66	89	1271	75	1552	91
18	95	1222	68	95	1365	76	1656	92
19	101	1333	70	101	1477	78	1766	93
20				107	1605	80	1884	94
21				94	1748	83	2013	96
22				98	1900	86	2158	98
23				102	2059	90	2335	102
24				108	2219	93	2548	106
25					2374	95	2804	112
26							3110	120
27							3464	128
28							3928	140
29							4409	152
30							5068	169
31							5850	189
32							6674	209
33							7503	227

Table 8. Fuel Data table of DDG 51 Class (FLT. IIA) Total ship fuel consumption (GPH) (with Stern Flap). From [7].

Research has been done identifying the most economical plant configuration to be used for a given speed. These recommended plant configurations should be used by the NFMS CONUS server to obtain an accurate fuel plan [8].

Once the fuel curve databases are populated on the NFMS CONUS server, then it is a simple table look up to determine the speed required to reach each waypoint, which will, in turn, determine how much fuel is burned per hour. Dividing the speed to reach each intermediate waypoint by the distance (both provided by the AOTSR route generator service) will yield how long the ship will take to reach each intermediate waypoint. Multiplying the time to reach the intermediate waypoint by the amount of fuel burned per hour will yield the amount of fuel burned to reach each intermediate waypoint. This amount of fuel burned to get to each intermediate waypoint is summed to get to the weight for the links between each identified refueling location in the transportation problem analysis (see Figure 11 for the mathematical representation).

From the information provided from the AOTSR route generator:

For a given link $\boldsymbol{L_{ij}}$

- Define intermediate waypoints Wk, k = 0,m with W_0 being the starting node i on link L_{ij}, and W_m being the ending node j on link L_{ij}.

For each intermediate waypoint $\boldsymbol{W_{k.}}$ in L_{ij}, let

- $\boldsymbol{A_k}$ = the speed used to get to intermediate waypoint W_k from W_{k-1} in nautical miles per hour (knots).
- $\boldsymbol{B}_k$ = the distance from intermediate waypoint W_{k-1} to Wk in nautical miles.
- $\boldsymbol{C_k}$ = Gallons of fuel burned per hour transiting from W_{k-1} to W_k. Note that $\boldsymbol{A_k}$ can be used to get $\boldsymbol{C_k}$ from the database fuel consumption charts for a given speed for a given ship class.
- $\boldsymbol{D}_k$ = Gallons of fuel used to transit from W_{k-1} to W_k.

$$D_k = (A_k \div B_k) \times C_k$$

$\boldsymbol{D}_{ij}$ = Gallons of fuel used across the entire link $\boldsymbol{L_{ij}}$

$$D_{ij} = \sum_k D_k$$

Figure 11. Mathematical pre-processing requirements.

B. MATHEMATICAL MODEL FOR SOLVING SHORTEST PATH

Once the link weights are determined by using the logic in Figure 11, a repeatable model will need to be used to derive the shortest path. This shortest path will be the most efficient or optimized route a ship should take based on fuel burned. Figure 12 is a well-known way to solve for the shortest path [9].

Let

1 = Source node, the designated, fixed starting node

S = Sink node, the designated, fixed ending node

X_{ij} = 1 if the link ij should be travelled, 0 otherwise

L_{ij} = Weight for link X_{ij}

$$\min_{X_{ij}} \sum_{ij} L_{ij} X_{ij}$$

Subject to

$$\sum_{j} X_{1j} = 1$$

$$\sum_{i} X_{in} - \sum_{j} X_{nj} = 0 \quad \forall n,\ i \neq 1,\ j \neq s$$

$$\sum_{i} X_{is} = -1$$

Figure 12. Generic mathematical model for solving shortest path.

C. SOLVING WITH MICROSOFT EXCEL: PROOF OF CONCEPT

Microsoft Excel contains a built-in solver that can optimize the model represented in Figure 12 for small problems, typically networks of 50 nodes or less. We present an example problem, based on hypothetical data, which will serve as a proof of concept for the fuel optimization model. The proof of concept may be accessed by clicking the paper clip icon visible on the lower left-hand corner of your screen. Ensure Adobe Acrobat is set up to open non-PDF attachments (Edit, Preferences, Trust Manager). Alternatively, you may save the Excel file to your hard drive in order to open it.

In our proof-of-concept example, a user on a DDG 51 Class ship is setting out to plan the fuel stops from a homeport in Norfolk, VA, to the Port of Mallorca, Spain, ending in Dubai. (We assume all DTG will be set to 1200z to simplify the math involved in calculating gallons for weights of links. This way, integral 24-hour days will be used.)

Waypoint Name	Latitude	Longitude	Arrive	Depart
Norfolk (1)	36°59’33”N	76°20’32”W	-	01 JAN 2011
Mallorca (4)	39°19’45”N	2°55’14”E	15 JAN 2011	18 JAN 2011
Dubai(9)	25°17’22”N	55°16’13”E	10 FEB 2011	-

Table 9. User Input to Proof of Concept.

From the data calls described above, the notional data in Table 10 is a representation of the information returned by the FSMD. To simplify calculations, the time spent refueling will be assumed to be zero even though in reality it takes approximately 2–3 hours to come alongside and refuel. Typical refueling speed is 13 knots at full power for restricted maneuvering. Using Table 8, it can be determined that a DDG will burn 1196 gallons of fuel per hour alongside. This is also typically on a course set into the seas for a smother refueling operation. This time spent refueling, therefore, causes an increase in speed necessary to get to the next waypoint on schedule, along with the excessive fuel consumption while at full power. In an actual application, these calculations should be taken into account so that the most accurate fuel usage estimates can be used to optimize a fuel plan.

Waypoint Name	Latitude	Longitude	Arrive	Depart
RAS (2)	37°68’34”N	10°49”17”W	12 JAN 2011	12 JAN 2011
RAS (3)	37°16’39”N	0°15’13”E	14 JAN 2011	14 JAN 2011
RAS (5)	32°41’28”N	26°28’29”E	24 JAN 2011	24 JAN 2011
Cyprus (6)	34°45’7”N	33°34’49”E	26 JAN 2011	26 JAN 2011
Djibouti (7)	11°29’1”N	43°13’56”E	02 FEB 2011	02 FEB 2011
RAS (8)	15°37’12”N	57°31’45”E	05 FEB 2011	05 FEB 2011

Table 10. Notional data returned by FSMD.

The transportation network diagram in Figure 13 can be derived by using the dates available for refueling. The numbers are sequential and do not necessarily require they be followed in order to determine the shortest path. It is important to note that the waypoint names would be resolved, as noted in Chapter III, with a database of known port names and locations. This ensures that only the port ID need be passed, minimizing bandwidth utilization. The numbers and names described in Tables 10 and 11 are numbered to better label the nodes on Figure 13.

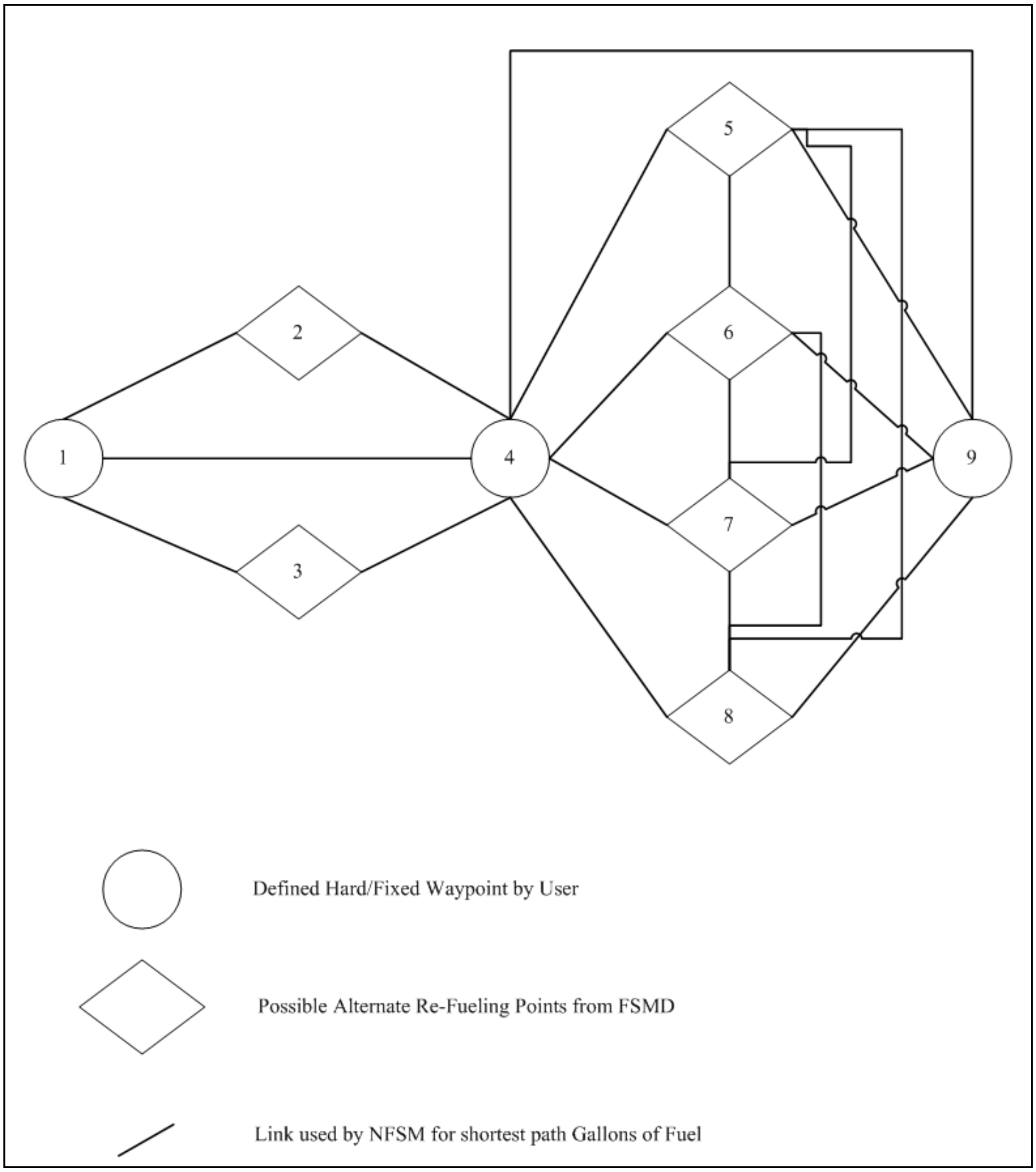

Figure 13. Transportation Network diagram of proof of concept problem.

Figure 14 shows a screen shot using Google Earth to approximate distances, avoiding land and taking direct routes. The tracks can be seen coming from Norfolk, Virginia / node 1 into refueling node 2. The subsequent nodes are labeled on Figure 14.

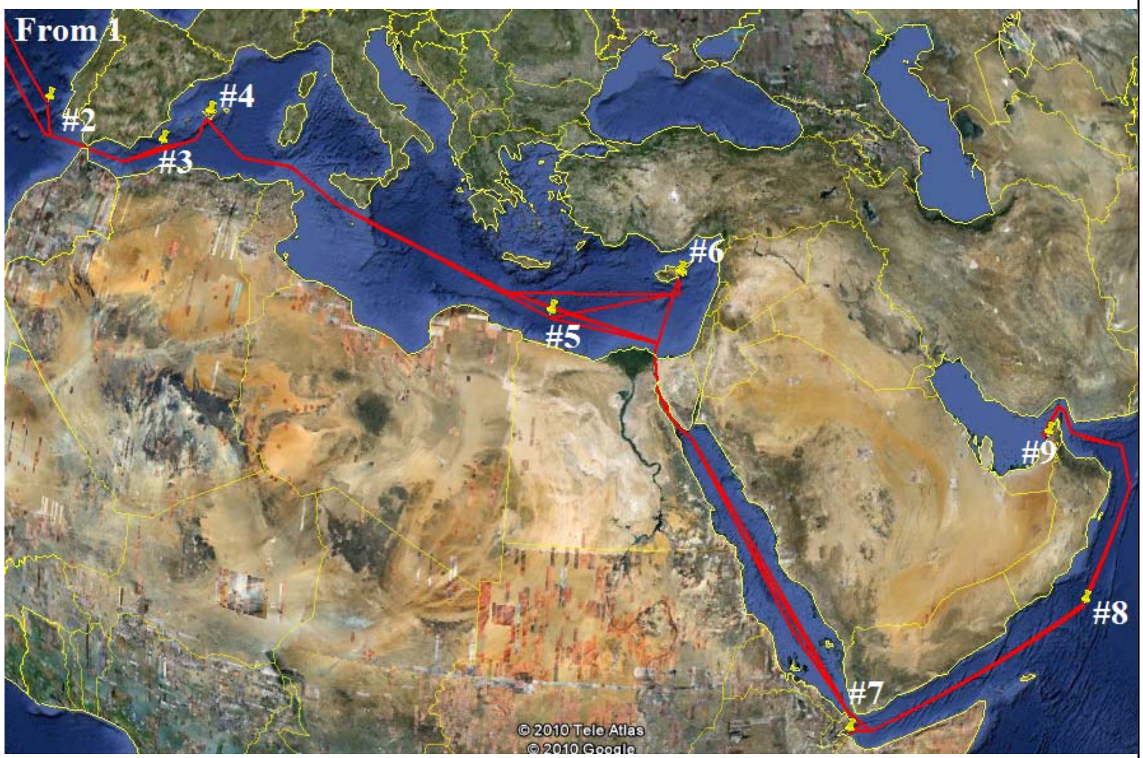

Figure 14. Proof of concept displayed on Google Earth.

Table 11 is a summary the distances, days, hours, speeds, fuel burn rates, and fuel consumptions of the proof of concept from Excel. The total fuel burned is a combination of the fuel used for moving the ship through the water from the gas turbine engines (GTE) and the fuel used by the gas turbine generators (GTG) to provide electricity. An average of 280 gallons per hour (GPH) was used for the GTG to take into account changing GTGs or operating on more than one GTG for short periods of time. The amount of fuel burned by the GTGs was found in the Shipboard Energy Conservation Guide [10]. Figure 15 is the fuel burn rate chart for DDG 51 class ships.

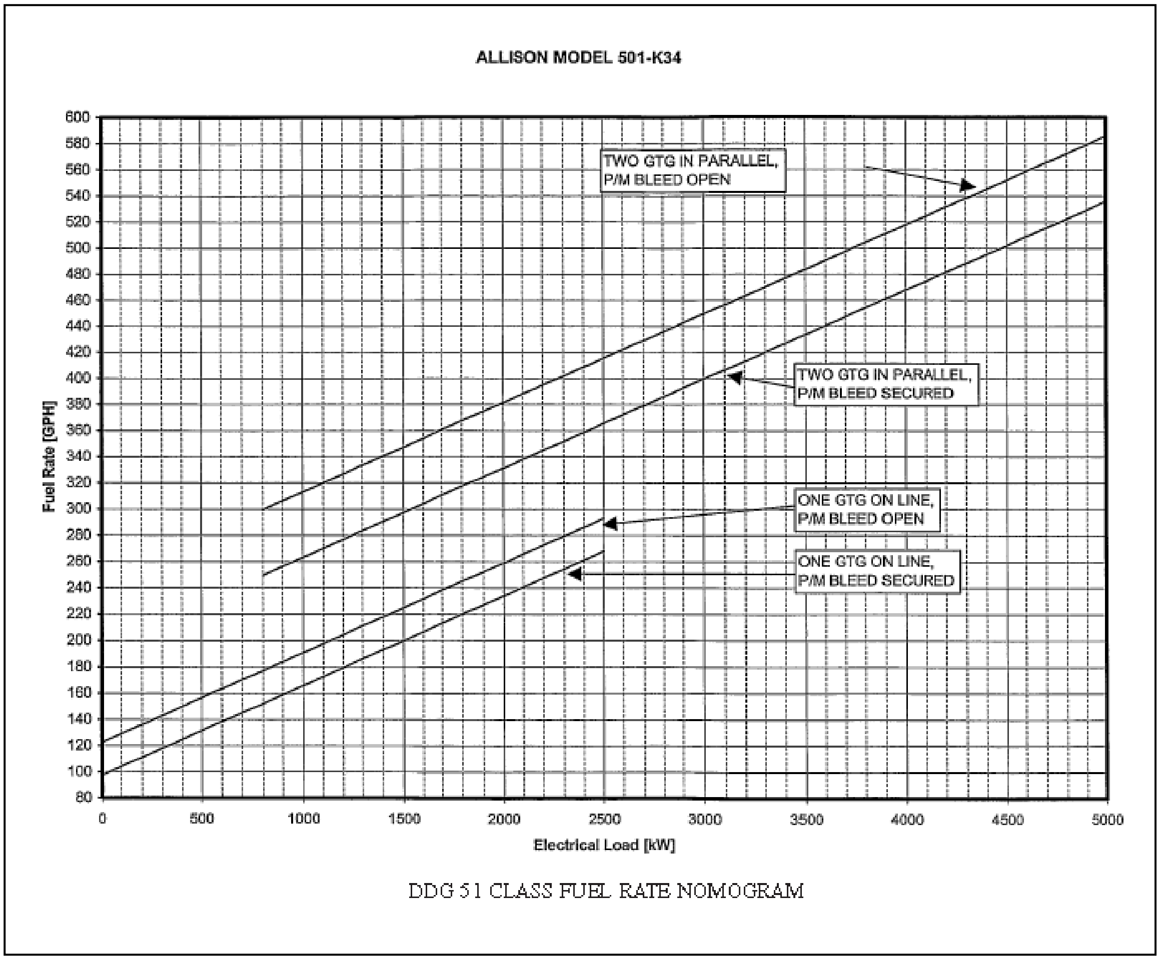

Figure 15. GTG fuel burn rate. From [10].

From	To	Distance (NM)	Days	Hours	Speed (knots)	GPH	Fuel burned GTE	Fuel burned GTG (Gallons)	Total Fuel Burned	Day Depart	Day Arrive	Speed Coefficein due to weath
1	4	3,868	14	336	11.5	748.77	251,588	94,080	345,668	1-Jan-11	15-Jan-11	1
4	9	4,722	22	528	8.9	653.87	345,244	147,840	493,084	18-Jan-11	10-Feb-11	1
1	2	3,082	11	264	11.7	753.33	198,880	73,920	272,800	1-Jan-11	12-Jan-11	1
1	3	3,672	13	312	11.8	757.97	236,485	87,360	323,845	1-Jan-11	14-Jan-11	1
2	4	795	3	72	11.0	727.05	52,347	20,160	72,507	12-Jan-11	15-Jan-11	1
3	4	197	1	24	8.2	635.33	15,248	6,720	21,968	14-Jan-11	15-Jan-11	1
4	5	1,227	6	144	8.5	642.95	92,585	40,320	132,905	18-Jan-11	24-Jan-11	1
4	6	1,613	8	192	8.4	640.36	122,949	53,760	176,709	18-Jan-11	26-Jan-11	1
4	7	2,950	14	336	8.8	648.30	217,828	94,080	311,908	18-Jan-11	2-Feb-11	1
4	8	3,739	17	408	9.2	659.67	269,146	114,240	383,386	18-Jan-11	5-Feb-11	1
5	9	3,497	16	384	9.1	659.67	253,314	107,520	360,834	24-Jan-11	10-Feb-11	1
6	9	3,371	14	336	10.0	688.72	231,411	94,080	325,491	26-Jan-11	10-Feb-11	1
7	9	1,846	8	192	9.6	675.20	129,639	53,760	183,399	2-Feb-11	10-Feb-11	1
8	9	979	5	120	8.2	632.90	75,948	33,600	109,548	5-Feb-11	10-Feb-11	1
5	6	395	2	48	8.2	635.33	30,496	13,440	43,936	24-Jan-11	26-Jan-11	1
5	7	1,723	8	192	9.0	653.87	125,543	53,760	179,303	24-Jan-11	2-Feb-11	1
5	8	2,395	11	264	9.1	656.74	173,380	73,920	247,300	24-Jan-11	5-Feb-11	1
6	7	1,640	6	144	11.4	739.87	106,541	40,320	146,861	26-Jan-11	2-Feb-11	1
6	8	2,393	9	216	11.1	727.05	157,042	60,480	217,522	26-Jan-11	5-Feb-11	1
7	8	875	3	72	12.2	777.24	55,961	20,160	76,121	2-Feb-11	5-Feb-11	1

Table 11. Summary of distances, days, hours, speeds, fuel burn rates, and fuel consumption for proof of concept transportation network from Microsoft Excel.

Waypoint Name	Latitude	Longitude	Arrive	Depart
Norfolk(1)	36°59'33"N	76°20'32" W"	-	1-Jan-11
Mallorca(4)	39°19'45"N	2°55'14"E	15-Jan-11	18-Jan-11
Dubai(9)	25°17'22"N	55°16'13" E	10-Feb-11	-

Table 12. Summary of user input for proof of concept in Microsoft Excel.

Waypoint Name	Latitude	Longitude	Arrive	Depart
RAS (2)	37°68'34"N	10°49"17"W	12-Jan-11	12-Jan-11
RAS (3)	37°16'39"N	0°15'13"E	14-Jan-11	14-Jan-11
RAS (5)	32°41'28"N	26°28'29"E	24-Jan-11	24-Jan-11
Cyprus (6)	34°45'7"N	33°34'49"E	26-Jan-11	26-Jan-11
Djibouti (7)	11°29'1"N	43°13'56"E	2-Feb-11	2-Feb-11
RAS (8)	15°37'12"N	57°31'45"E	5-Feb-11	5-Feb-11

Table 13. Summary of returned data from FSMD in Microsoft Excel.

Tables 11, 12 and 13 are derived using the green cells as givens from the proof of concept description. Table 12 calculations are as follows:

- Distance is measured from Google Earth shown in Figure 14.
- Days used the Excel function = DAYS360(Day Depart, Day Arrive)
- Hours = Days * 24
- Speed = (Distance/Hours) * Speed Coefficient Due to Weather
- GPH = VLOOKUP(sending speed, returning GPH from Table 14)
- Fuel Burned GTG = Assumed GTG burn fuel average * Hours
- Fuel Burned GTE = GPH * Hours
- Total Fuel Burned = Fuel Burned GTG + Fuel Burned GTE

In order to obtain a table look up accurate to tenths of a knot in Excel, a nonlinear regression must be run on the data from Table 8. By first plotting the data in Table 8, shown by the red line in Figure 16, a 3rd order polynomial regression was used to derive the black dashed line in Figure 16. The 3rd order polynomial regression result is

$$y = 0.098x^3 + 1.4091x^2\ 7.5611x + 571.46.$$

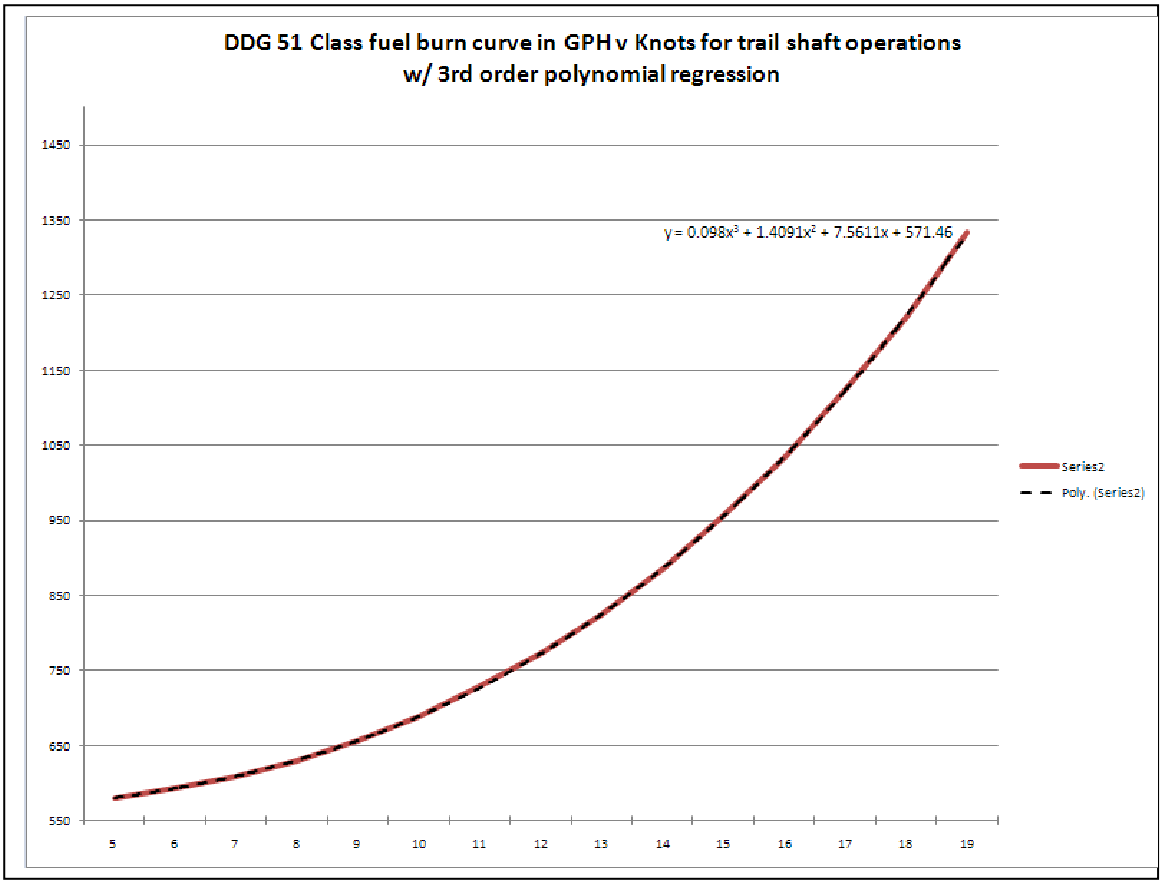

Figure 16. Graph of 3rd order polynomial regression compared to original graph of DDG 51 Fuel Burn Table.

An offset must be applied to the regression since the plot starts at x = 5, whereas, the regression starts at x = 0. Table 14 is an excerpt from the table in Microsoft Excel that served as the look-up table in the VLOOKUP function.

GPH from Table 8	Ship Speed Knots	GPH from 3rd order polynomial regression	Offset for chart x axis starts at 5 not 0
581	5	580.53	1
	5.1	581.61	1.1
	5.2	582.73	1.2
	5.3	583.89	1.3
	5.4	585.08	1.4
	5.5	586.30	1.5
	5.6	587.57	1.6
	5.7	588.87	1.7
	5.8	590.21	1.8
	5.9	591.59	1.9
593	6	593.00	2
	6.1	594.46	2.1
	6.2	595.96	2.2
	6.3	597.50	2.3
	6.4	599.08	2.4
	6.5	600.70	2.5
	6.6	602.37	2.6
	6.7	604.08	2.7
	6.8	605.83	2.8
	6.9	607.63	2.9
609	7	609.47	3
	7.1	611.36	3.1
	7.2	613.30	3.2
	7.3	615.28	3.3
	7.4	617.31	3.4
	7.5	619.39	3.5
	7.6	621.51	3.6
	7.7	623.69	3.7
	7.8	625.92	3.8
	7.9	628.19	3.9
630	8	630.52	4
	8.1	632.90	4.1
	8.2	635.33	4.2
	8.3	637.82	4.3
	8.4	640.36	4.4
	8.5	642.95	4.5

Table 14. Table used for VLOOKUP Excel function to determine GPH from knots in Proof of Concept.

The next step is to define the linear program decision variables, objective function, and flow balance equations. For this proof of concept, the enumerated decision variables, objective function, and the flow balance equations are given in Figure 17.

Decision Variables = X_{ij} which nodes to takes to get through the route.

Objective Function (in gallons):

Min(345,668 X_{14} * 493,084 X_{49} * 272,800 X_{12} * 323,845 X_{13} * 72,507 X_{24} * 21,968 X_{34} * 132,905 X_{45} * 176,709 X_{46} * 311,908 X_{47} * 383,386 X_{48} * 360,843 X_{59} * 325,491 X_{69} * 183,399 X_{79} * 109,548 X_{89} * 43,936 X_{56} * 179,303 X_{57} * 247,300 X_{58} * 146,861 X_{67} * 217,522 X_{68} * 76,121 X_{78} * 345,668 X_{41} * 493,084 X_{94} * 272,800 X_{21} * 323,845 X_{31} * 72,507 X_{42} * 21,968 X_{43} * 132,905 X_{54} * 176,709 X_{64} * 311,908 X_{74} * 383,386 X_{84} * 360,843 X_{95} * 325,491 X_{96} * 183,399 X_{97} * 109,548 X_{98} * 43,936 X_{65} * 179,303 X_{75} * 247,300 X_{85} * 146,861 X_{76} * 217,522 X_{86} * 76,121 X_{87})

Flow Balance Equations:

<u>Node</u>	<u>Equation</u>
1	$(X_{21} + X_{31} + X_{41}) – (X_{12} + X_{31} + X_{14}) = -1$
2	$(X_{12} + X_{42}) – (X_{21} + X_{24}) = 0$
3	$(X_{13} + X_{43}) – (X_{31} + X_{34}) = 0$
4	$(X_{14} + X_{24} + X_{34} + X_{94} + X_{54} + X_{64} + X_{74} + X_{84}) – (X_{41} + X_{42} + X_{43} + X_{49} + X_{45} + X_{46} + X_{47} + X_{48}) = 0$
5	$(X_{45} + X_{95} + X_{65} + X_{75} + X_{85}) – (X_{54} + X_{59} + X_{56} + X_{57} + X_{58}) = 0$
6	$(X_{46} + X_{96} + X_{56} + X_{76} +X_{86}) – (X_{64} + X_{69} + X_{65} + X_{67} +X_{68}) = 0$
7	$(X_{47} + X_{97} + X_{57} + X_{67} + X_{87}) – (X_{74} + X_{79} + X_{75} + X_{76} + X_{78}) = 0$
8	$(X_{48} + X_{98} + X_{58} + X_{68} + X_{78}) – (X_{84} + X_{89} + X_{85} + X_{86} + X_{87}) = 0$
9	$(X_{49} + X_{59} + X_{69} + X_{79} + X_{89}) – (X_{94} + X_{95} + X_{96} + X_{97} + X_{98}) = 1$

Figure 17. Decision Variable, Objective Function, and Flow Balance Equations for Proof of Concept.

Once the decision variables, objective function and flow balance equations are specified, Microsoft Excel's solver can be used to find the shortest path. The light green cell in Table 15 is calculated using the SUMPRODUCT function on the flows and gallons tables. The gallons table in Table 15 is populated using the Total Fuel Burned column in Table 11; however, since DDGs have a seawater compensated fuel system, some percentage of fuel must be maintained at all times to ensure seawater is not accidentally injected into the engines. This percentage is represented in the darker green square labeled “percent to maintain” in Table 15. A DDG holds approximately 450,000 gallons of Diesel Fuel Marine (DFM); however, Table 15 allows this number to be parameterized depending upon ship class. Recall also that the fuel burn chart will change depending upon the ship class so, in the general solution, selecting the ship class should automatically change the reference data used appropriately. Using the parameters “percentage to maintain” and “total fuel capacity,” a filter is applied prior to populating the gallons table. This filter is applied using an if statement in Excel as follows:

IF (gallons_burned<=max_fuel_used_per_link,

THEN gallons_burned,

ELSE 10000000000).

The default value 10,000,000,000 is used to make the link weight so large that when compared to the estimated fuel burned, it becomes unavailable as a possible solution. Also, in Table 15 there is another variable denoted in darker green, “assumed GTG burn fuel average,” for which a default value of 280 is used as an average from the incentivized energy conservation program. This variable also is a model parameter that can be adjusted if a given ship tends to use more fuel, and then propagated to Table 11.

Flow balance equations					
Node	**Flow in**	**Flow out**	**Net flow**	**Sign**	**RHS**
Node 1	0.0	1.0	-1.0	=	-1
Node 4	1.0	1.0	0.0	=	0
Node 9	1.0	0.0	1.0	=	1
Node 2	1.0	1.0	0.0	=	0
Node 3	0.0	0.0	0.0	=	0
Node 5	1.0	1.0	0.0	=	0
Node 6	0.0	0.0	0.0	=	0
Node 7	0.0	0.0	0.0	=	0
Node 8	1.0	1.0	0.0	=	0

Flows:	To									
From	N-1	N-4	N-9	N-2	N-3	N-5	N-6	N-7	N-8	Flow out
Node 1	0.0	0.0	0.0	1.0	0.0	0.0	0.0	0.0	0.0	1.
Node 4	0.0	0.0	0.0	0.0	0.0	1.0	0.0	0.0	0.0	1.
Node 9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.
Node 2	0.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.
Node 3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.
Node 5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	1.
Node 6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.
Node 7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.
Node 8	0.0	0.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	1.
Flow in	0.0	1.0	1.0	1.0	0.0	1.0	0.0	0.0	1.0	

Gallons:	To								
From	N-1	N-4	N-9	N-2	N-3	N-5	N-6	N-7	N-8
Node 1	##########	345,668	#########	272,800	323,845	######	######	########	######
Node 4	345,668	#########	#########	72,507	21,968	132,905	176,709	311,908	383,386
Node 9	##########	#########	#########	#########	##########	360,834	325,491	183,399	109,548
Node 2	272,800	72,507	#########	#########	##########	######	######	########	######
Node 3	323,845	21,968	#########	#########	##########	######	######	########	######
Node 5	##########	132,905	360,834	#########	##########	######	43,936	179,303	247,300
Node 6	##########	176,709	325,491	#########	##########	43,936	######	146,861	217,522
Node 7	##########	311,908	183,399	#########	##########	179,303	146,861	########	76,121
Node 8	##########	383,386	109,548	#########	##########	247,300	217,522	76,121	######

Least Fuel =	835,061	
Fuel Capacity =	450,000	<-Fuel Capacity of Ship (variable per class)
Percent to maintain =	10%	<-Fuel Percentage to maintain onboard can set to mechanical failure or CO standing o
Max Fuel Used per link =	405,000	
Assumed GTG burn fuel average =	280	

Table 15. Proof of Concept Solution in Microsoft Excel.

Once the given darker green cells are populated, the solver parameters in Figure 18 can be used to derive the shortest path solution. The target cell is the light green cell in Table 15 labeled Least Fuel. It is set equal to Min because NFMS wants to minimize the amount of fuel used to achieve the shortest path, subject to the constraints in the array of the flow balance equations, which are tied into the flows table depicted in light blue in Table 15.

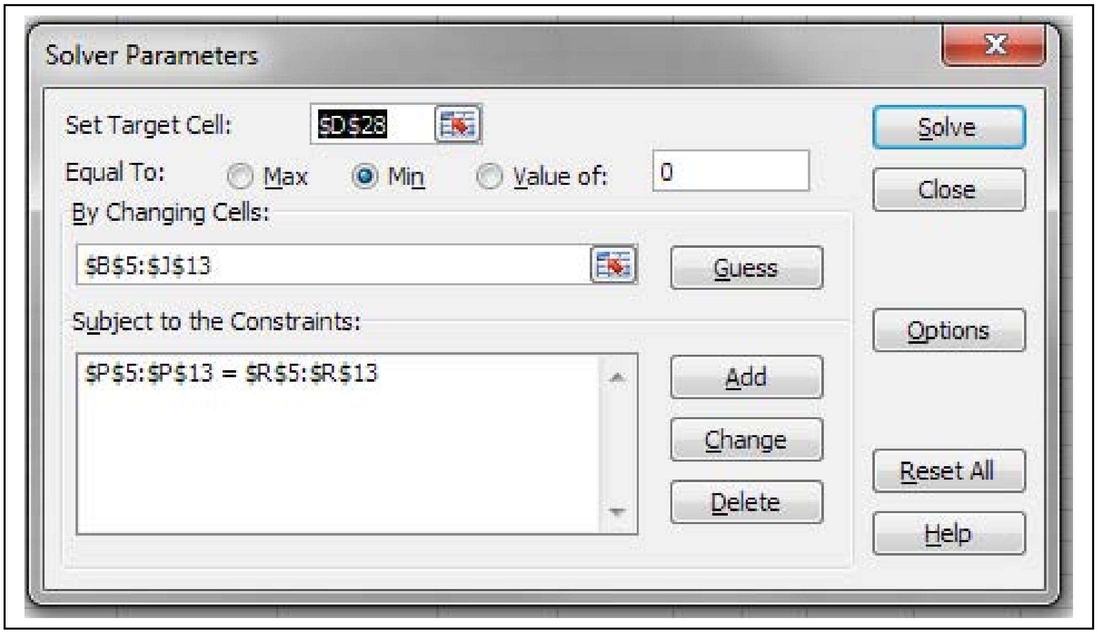

Figure 18. Microsoft Excel solver parameters for NFMS Proof of Concept.

D. INTERPRETING RESULTS

Observing the flow balance equations in Table 15, it can be seen the flows in and out for the nodes equate to the same outcome in the flow balance equations in Figure 17. This means that all constraints and balances are met and one unit will have traveled from Node 1 to Node 9.

One must look at the yellow shaded areas to determine which path the unit must take in order to travel along the shortest path, using 835,061 gallons of fuel in the process. Here, the model solves the problem by having the ship travel along the following route from node 1 → node 2 → node 4 → node 5 → node 8 → node 9. In real-world terms translating from Tables 12 and 13, this corresponds to the fuel plan Norfolk → RAS #2 → Mallorca → RAS #5 → RAS #8 →Dubai.

E. VALIDATION (NFMS AGAINST PIM MODEL)

With the weather coefficients shown in Table 11 set equal to 1, the shortest path algorithm is essentially doing a shortest path analysis on the PIM model. Weather has not been taken into account. However, by appropriately changing the weather coefficient weight to simulate a storm along a track, which would cause a ship following that track to speed up and use more fuel, the benefits of a system such as NFMS to the fleet can be seen clearly. In our next scenario, the weather coefficient is increased from 1 to 1.1 on the links from Node 1 to 2 and Node 4 to 5, both previous links in the first shortest path. The change can be seen in Table 16. Also, the speed changes from 11.7 to 12.8, and 8.5 to 9.4 knots, just 1 knot difference in each case. This corresponds to the scenario described in Chapter III where the NFMS CONUS server performed a 24-hour update on an optimal plan, and the weather changed, in turn causing the inputs to the shortest path algorithm to change.

From	To	Distance (NM)	Days	Hours	Speed (knots)	GPH	Fuel burned GTE	Fuel burned GTG (Gallons)	Total Fuel Burned	Day Depart	Day Arrive	Speed Coefficeint due to weather
1	4	3,868	14	336	11.5	748.77	251,588	94,080	345,668	1-Jan-11	15-Jan-11	1
4	9	4,722	22	528	8.9	653.87	345,244	147,840	493,084	18-Jan-11	10-Feb-11	1
1	2	3,082	11	264	12.8	813.90	214,870	73,920	288,790	1-Jan-11	12-Jan-11	1.1
1	3	3,672	13	312	11.8	757.97	236,485	87,360	323,845	1-Jan-11	14-Jan-11	1
2	4	795	3	72	11.0	727.05	52,347	20,160	72,507	12-Jan-11	15-Jan-11	1
3	4	197	1	24	8.2	635.33	15,248	6,720	21,968	14-Jan-11	15-Jan-11	1
4	5	1,227	6	144	9.4	665.71	95,862	40,320	136,182	18-Jan-11	24-Jan-11	1.1
4	6	1,613	8	192	8.4	640.36	122,949	53,760	176,709	18-Jan-11	26-Jan-11	1
4	7	2,950	14	336	8.8	648.30	217,828	94,080	311,908	18-Jan-11	2-Feb-11	1
4	8	3,739	17	408	9.2	659.67	269,146	114,240	383,386	18-Jan-11	5-Feb-11	1
5	9	3,497	16	384	9.1	659.67	253,314	107,520	360,834	24-Jan-11	10-Feb-11	1
6	9	3,371	14	336	10.0	688.72	231,411	94,080	325,491	26-Jan-11	10-Feb-11	1
7	9	1,846	8	192	9.6	675.20	129,639	53,760	183,399	2-Feb-11	10-Feb-11	1
8	9	979	5	120	8.2	632.90	75,948	33,600	109,548	5-Feb-11	10-Feb-11	1
5	6	395	2	48	8.2	635.33	30,496	13,440	43,936	24-Jan-11	26-Jan-11	1
5	7	1,723	8	192	9.0	653.87	125,543	53,760	179,303	24-Jan-11	2-Feb-11	1
5	8	2,395	11	264	9.1	656.74	173,380	73,920	247,300	24-Jan-11	5-Feb-11	1
6	7	1,640	6	144	11.4	739.87	106,541	40,320	146,861	26-Jan-11	2-Feb-11	1
6	8	2,393	9	216	11.1	727.05	157,042	60,480	217,522	26-Jan-11	5-Feb-11	1
7	8	875	3	72	12.2	777.24	55,961	20,160	76,121	2-Feb-11	5-Feb-11	1

Table 16. Adding weather to tracks by changing weather coefficients.

Without running the solver again, the formulas embedded into the spreadsheet change the number of gallons used from 835,061 gallons to 854,328 gallons. This represents an increase of 19,267 gallons corresponding to an increase of 1 knot across two of the five links in the shortest path returned. If we now rerun the solver with the new given data, a new shortest path solution results, as shown in Table 17.

Flow balance equations					
Node	Flow in	Flow out	Net flow	Sign	RHS
Node 1	0.0	1.0	-1.0	=	-1
Node 4	1.0	1.0	0.0	=	0
Node 9	1.0	0.0	1.0	=	1
Node 2	0.0	0.0	0.0	=	0
Node 3	0.0	0.0	0.0	=	0
Node 5	0.0	0.0	0.0	=	0
Node 6	0.0	0.0	0.0	=	0
Node 7	0.0	0.0	0.0	=	0
Node 8	1.0	1.0	0.0	=	0

Flows:	To									
From	N-1	N-4	N-9	N-2	N-3	N-5	N-6	N-7	N-8	Flow out
Node 1	0.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0
Node 4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	1.0
Node 9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Node 2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Node 3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Node 5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Node 6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Node 7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Node 8	0.0	0.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0
Flow in	0.0	1.0	1.0	0.0	0.0	0.0	0.0	0.0	1.0	

Gallons:	To								
From	N-1	N-4	N-9	N-2	N-3	N-5	N-6	N-7	N-8
Node 1	##########	345,668	#########	288,790	323,845	######	######	########	######
Node 4	345,668	#########	#########	72,507	21,968	136,182	176,709	311,908	383,386
Node 9	##########	#########	#########	#########	##########	360,834	325,491	183,399	109,548
Node 2	288,790	72,507	#########	#########	##########	######	######	########	######
Node 3	323,845	21,968	#########	#########	##########	######	######	########	######
Node 5	##########	136,182	360,834	#########	##########	######	43,936	179,303	247,300
Node 6	##########	176,709	325,491	#########	##########	43,936	######	146,861	217,522
Node 7	##########	311,908	183,399	#########	##########	179,303	146,861	########	76,121
Node 8	##########	383,386	109,548	#########	##########	247,300	217,522	76,121	######

Least Fuel =	838,602	
Fuel Capacity =	450,000	<-Fuel Capacity of Ship (variable per class)
Percent to maintain =	10%	<-Fuel Percentage to maintain onboard can set to mechanical failure or CO standing ord
Max Fuel Used per link =	405,000	
Assumed GTG burn fuel average =	280	

Table 17. New shortest path solution due to weather coefficient changes.

Examining the flow balance equations in Table 17 reveals that this is a feasible solution that meets the constraints. Here, the new solution can be seen in the yellow highlighted cells indicating a 1 for each link taken: node 1 → node 4 → node 8 → node 9. This translates to a shortest fuel plan from Norfolk → Mallorca → RAS #8 → Dubai. The new optimal solution still reaches the required port visits on time; however, it burns only 838,602 gallons of fuel. Comparing this to the 854,328 gallons required from changing the weather coefficients on the old optimal solution, we see a savings of 15,726 gallons. By using the NFMS model, one can manage weather increasing the cost of fuel buy finding more efficient refueling nodes. By changing our fuel plan dynamically as weather data changes, rather than adhering to the static plan, there was only an increase in fuel consumption of 3,541 gallons due to weather.

The NFMS model as shown uses a fuel percentage of 10% to maintain in reserve. This would be similar to a set mechanical requirement for the seawater compensated fuel system onboard DDG's. However, if the CO wants to maintain reserve stock to mitigate the risk of running out of fuel, this should be a parameter in the NFMS model. In our next scenario, we examine the effects of such a change. In this case, we use the weather coefficients on the links from nodes 1 to 2 and nodes 4 to 5, as shown in Table 16 but increase the "percent to maintain" to 30%, as shown in Table 18.

Flows:	To									
From	N-1	N-4	N-9	N-2	N-3	N-5	N-6	N-7	N-8	Flow out
Node 1	0.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0
Node 4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	1.0
Node 9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Node 2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Node 3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Node 5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Node 6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Node 7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Node 8	0.0	0.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0
Flow in	0.0	1.0	1.0	0.0	0.0	0.0	0.0	0.0	1.0	

Gallons:	To								
From	N-1	N-4	N-9	N-2	N-3	N-5	N-6	N-7	N-8
Node 1	##########	#########	#########	288,790	##########	######	######	########	######
Node 4	##########	#########	#########	72,507	21,968	136,182	176,709	311,908	######
Node 9	##########	#########	#########	#########	##########	######	######	183,399	109,548
Node 2	288,790	72,507	#########	#########	##########	######	######	########	######
Node 3	##########	21,968	#########	#########	##########	######	######	########	######
Node 5	##########	136,182	#########	#########	##########	######	43,936	179,303	247,300
Node 6	##########	176,709	#########	#########	##########	43,936	######	146,861	217,522
Node 7	##########	311,908	183,399	#########	##########	179,303	146,861	########	76,121
Node 8	##########	#########	109,548	#########	##########	247,300	217,522	76,121	######

Least Fuel =	#########	
Fuel Capacity =	450,000	<-Fuel Capacity of Ship (variable per class)
Percent to maintain =	30%	<-Fuel Percentage to maintain onboard can set to mechanical failure or CO standing orders
Max Fuel Used per link =	315,000	
Assumed GTG burn fuel average =	280	

Table 18. Changing fuel percent to maintain form 10% to 30%.

Examining Table 18, it can be seen that number signs appear in the “least fuel” cell. This signifies that the shortest path solution from the previous example is no longer valid as one or more link weights now exceed the maximum fuel (315,000 gallons) allowed per link. Therefore, the solver must be run again, given the user’s input requirement to maintain a larger fuel reserve, to find a new shortest path that does not violate any constraints. The results can be seen in Table 19.

Flows:	To									
From	N-1	N-4	N-9	N-2	N-3	N-5	N-6	N-7	N-8	Flow out
Node 1	0.0	0.0	0.0	1.0	0.0	0.0	0.0	0.0	0.0	1.0
Node 4	0.0	0.0	0.0	0.0	0.0	1.0	0.0	0.0	0.0	1.0
Node 9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Node 2	0.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0
Node 3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Node 5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	1.0
Node 6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Node 7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Node 8	0.0	0.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0
Flow in	0.0	1.0	1.0	1.0	0.0	1.0	0.0	0.0	1.0	

Gallons:	To								
From	N-1	N-4	N-9	N-2	N-3	N-5	N-6	N-7	N-8
Node 1	##########	#########	#########	288,790	##########	######	######	########	######
Node 4	##########	#########	#########	72,507	21,968	136,182	176,709	311,908	######
Node 9	##########	#########	#########	#########	##########	######	######	183,399	109,548
Node 2	288,790	72,507	#########	#########	##########	######	######	########	######
Node 3	##########	21,968	#########	#########	##########	######	######	########	######
Node 5	##########	136,182	#########	#########	##########	######	43,936	179,303	247,300
Node 6	##########	176,709	#########	#########	##########	43,936	######	146,861	217,522
Node 7	##########	311,908	183,399	#########	##########	179,303	146,861	########	76,121
Node 8	##########	#########	109,548	#########	##########	247,300	217,522	76,121	######

Least Fuel =	854,328	
Fuel Capacity =	450,000	<-Fuel Capacity of Ship (variable per class)
Percent to maintain =	30%	<-Fuel Percentage to maintain onboard can set to mechanical failure or CO standing orders
Max Fuel Used per link =	315,000	

Table 19. Results of running solver with weather coefficients, and new fuel percentage requirement.

Now the target cell, the light green cell, labeled “least fuel,” has a solution as denoted by the yellow highlighted cells: node 1 → node 2 → node 4 → node 5 → node 8 → node 9. The new optimal fuel plan translates to Norfolk → RAS #2 → Mallorca → RAS #5 → RAS#8 → Dubai. This is the same solution from the original example prior to adding the weather coefficients with the same least fuel amount of 854,328 gallons. Therefore, by changing the “percent to maintain” onboard from 10% to 30% a tradeoff has occurred. The CO now knows the cost to mitigate the risk of running out of fuel is an additional 15,726 gallons of fuel.

We can see from the scenarios presented above that the NFMS provides valuable tradeoff analyses unavailable in the PIM model. The ability to evaluate and compare alternative plans is the "value added" from developing a decision support system such as NFMS. Once a prototype NFMS has been implemented, detailed sensitivity analyses ("what if" scenarios) can be conducted, possibly in conjunction with discrete event simulation models, to further measure the benefits of NFMS. This is a promising avenue for future research efforts.

F. ADDITIONAL CONSIDERATIONS

There are over 200 ships in today's Navy. If each ship is continually rerunning fuel plans for analysis, daily for fuel plans in operation and twice daily for fuel plans under development, this may result in a large processing load on the NFMS CONUS server. It should also be noted that the example used for the proof of concept is a simple static one to demonstrate how NFMS model and its associated shortest path algorithm can work. Once the FSMD is populated with all the possible refueling nodes, the transportation network size could easily reach in the hundreds. Using Excel's linear programming feature is not going to be an efficient technique for the shortest path when hundreds of nodes are involved, dynamically changing, on a given transportation network. By using the dual theorem, Dijkstra's algorithm can be used to achieve the same solution in a much more efficient way [11], and should be used as the baseline algorithm for NFMS.

Even using Dijkstra's algorithm to increase efficiency, processing time may be lengthy. Although Dijkstra's algorithm runs in polynomial time ($O(n^2)$), where n is the number of nodes in the network) a large-preprocessing time is needed to retrieve and format the data for the algorithm, and the network itself may grow in a nonpolynomial fashion, when many alternative paths exist. Therefore, priorities should be assigned to the types of optimizations being calculated. If a user input change occurs in the NFMS, it should be given top priority since this means that an operational fuel plan is not being followed correctly, and thus, more fuel has been burned than expected or the ship's operational schedule has changed and the fixed port visits have changed. This signals an unusual occurrence that should be assigned the highest priority, since a ship is underway and runs the highest risk of running out of fuel and has an urgent need for a new fuel plan.

Second-level priority should be given to the 24-hour update process, where NFMS checks for port visit changes and/or weather changes that could impact the optimal fuel plan. This situation is where the most gallons of fuel can potentially be saved in the long run. By taking advantage of following seas, avoiding rougher waters, and discovering new optimal fueling locations, a more efficient path can be followed. Routine processing should be used for planning purposes of future fuel plans not in operation. Since these ships are inport and planning ahead of time, a delay in returning an optimal fuel plan is acceptable compared to the risk associated with the other two priorities.

We now developed and defined the base algorithm at the heart of NFMS. Preprocessing will be required to convert the units given to the link weights in gallons of the transportation network. Microsoft Excel was used as a tool to solve for shortest path. This provided a means to do a sensitivity analysis changing the inputs and showing the true value NFMS can be to the fleet. Finally, since NFMS is expected to be highly utilized, priorities for processing should be established. Next, we will discuss the user interfaces for NFMS.

THIS PAGE INTENTIONALLY LEFT BLANK

V. USER INTERFACES

A. GUI INTERFACES

The user interface of a decision-support system application is a critical success factor in its eventual adoption. The intuitive nature of the interface and ease of use defines the usability of a system, and its continued use in service. Therefore, the following use-cases and associated screen captures provide some insight into the type of intuitive interfaces NFMS should support.

1. Map-Based Interfaces

Since NFMS is working with fuel plans for ocean voyages, the best interface to visually describe a plan is a map-based interface. This interface should be scalable, provide a legend for the symbology used, and use a granularly shaded line to depict fuel percentages. Figure 19 shows a mock-up of an interface using Google Earth as the background for the plan.

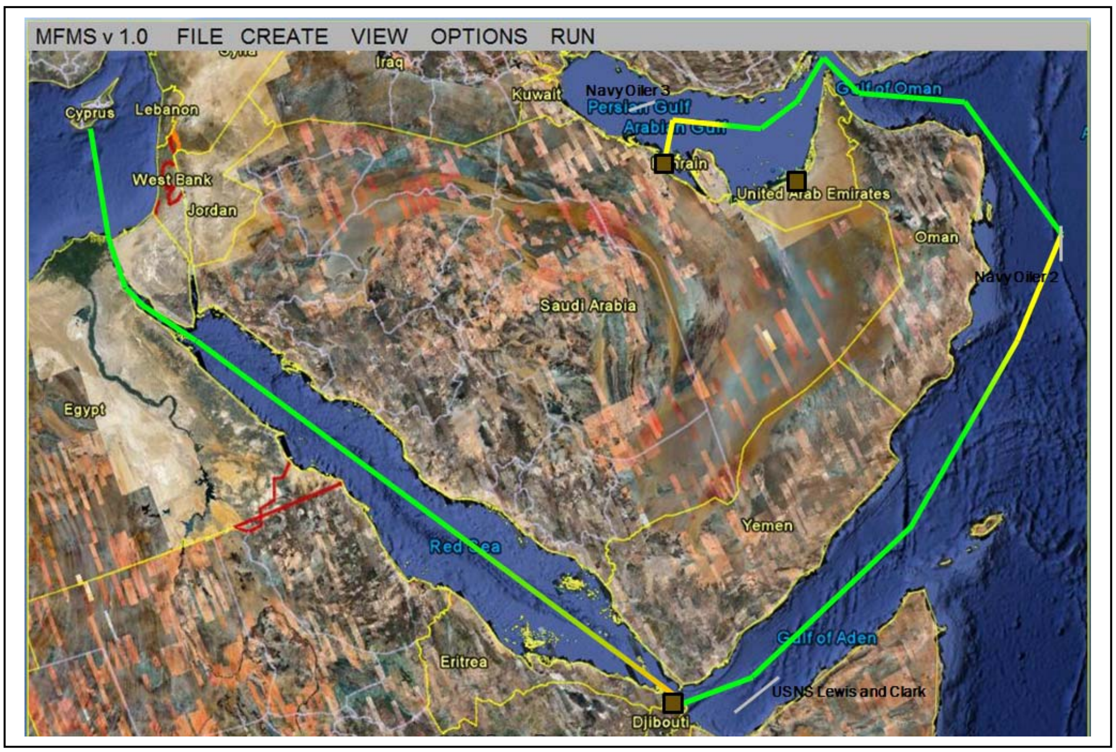

Figure 19. Example 1 of map-based interface.

In Figure 19, it can be clearly seen that the plan entails going from Cyprus to Djibouti to Navy Oiler 2 to Bahrain. This track is shaded from green to yellow to depict fuel percentage. As a ship follows a track, its fuel will be depleted, the extent to which is represented by the color of the track. Each time the track intercepts a refueling location, the color changes from its current status to green, indicating that the ship has refueled. Known refueling ports in the area are represented by brown squares, and RAS rendezvous locations with oilers by gray lines.

Track shading should be based on the refueling percentage onboard. The track color should be displayed as solid yellow at 50% or less of the difference between full refueling and the amount of fuel the CO's decides should remain onboard. For example, if the CO wishes to always maintain 30% fuel onboard, then the line should turn yellow at 50% of 100% to 30% scale or 65% of actual fuel onboard. The line should turn solid red when fuel is estimated to reach the 30% level. Once the fuel reaches below the safe to operate level for seawater compensated fuel systems, the line should turn black, indicating that the ship should not operate beyond that point.

Figure 20 represents a fuel burn chart view that should be a selection from the view menu. In this display, the amount of fuel is displayed on the Y-axis and either increases or decreases as a function of time across the X-axis. This will give decision makers another way of determining whether they are on track with the current plan, or if an alternate plan needs to be created.

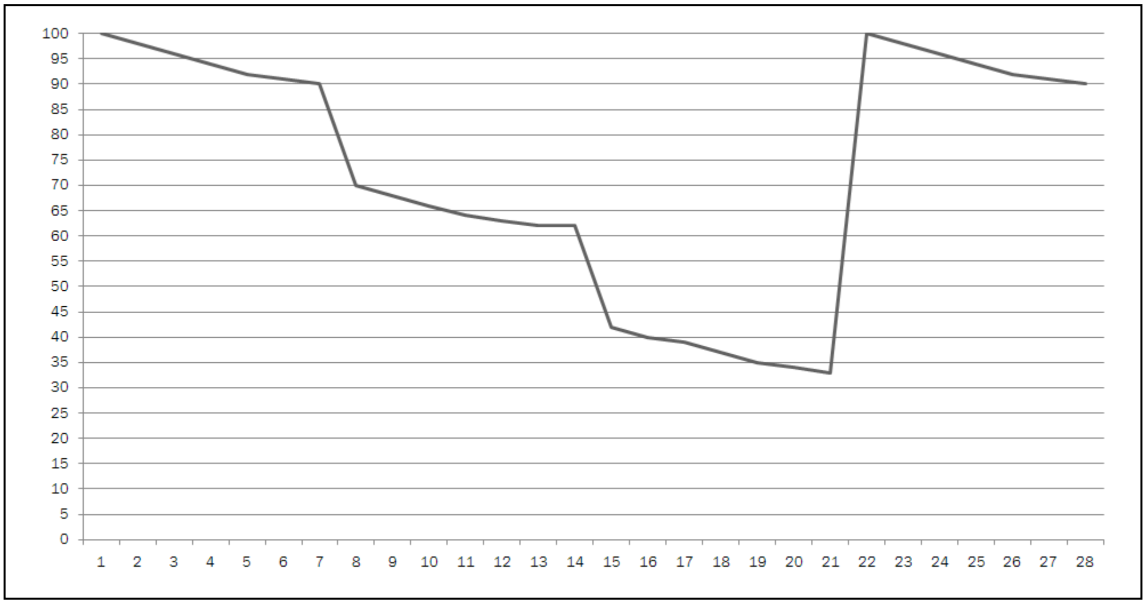

Figure 20. Notional fuel burn chart view in NFMS.

2. Text Data Input Interface

Inputting a large amount of text, especially latitudes and longitudes, can be a lengthy endeavor; however; based on the schema described in Chapter III, the amount of text entered by the user will be limited, once a list of known ports is established, else a latitude and longitude for each fixed waypoint would need to be entered each time a new fuel plan request is made. This is important for two reasons:

1. The more users are required to input numbers, the more often they make mistakes, which can compromise the system with incorrect data that, in turn, may provide the decision maker invalid results;

2. If the numbers need to be typed in manually each time, that is extra information that must be transmitted this in turn consumes bandwidth. Therefore, when a user adds a port to the plan, a selection box populated by the known port database should be available, as well as a standard calendar input scheme, so the user does not mistakenly input the incorrect data. An example of this type of input can be seen in Figure 21.

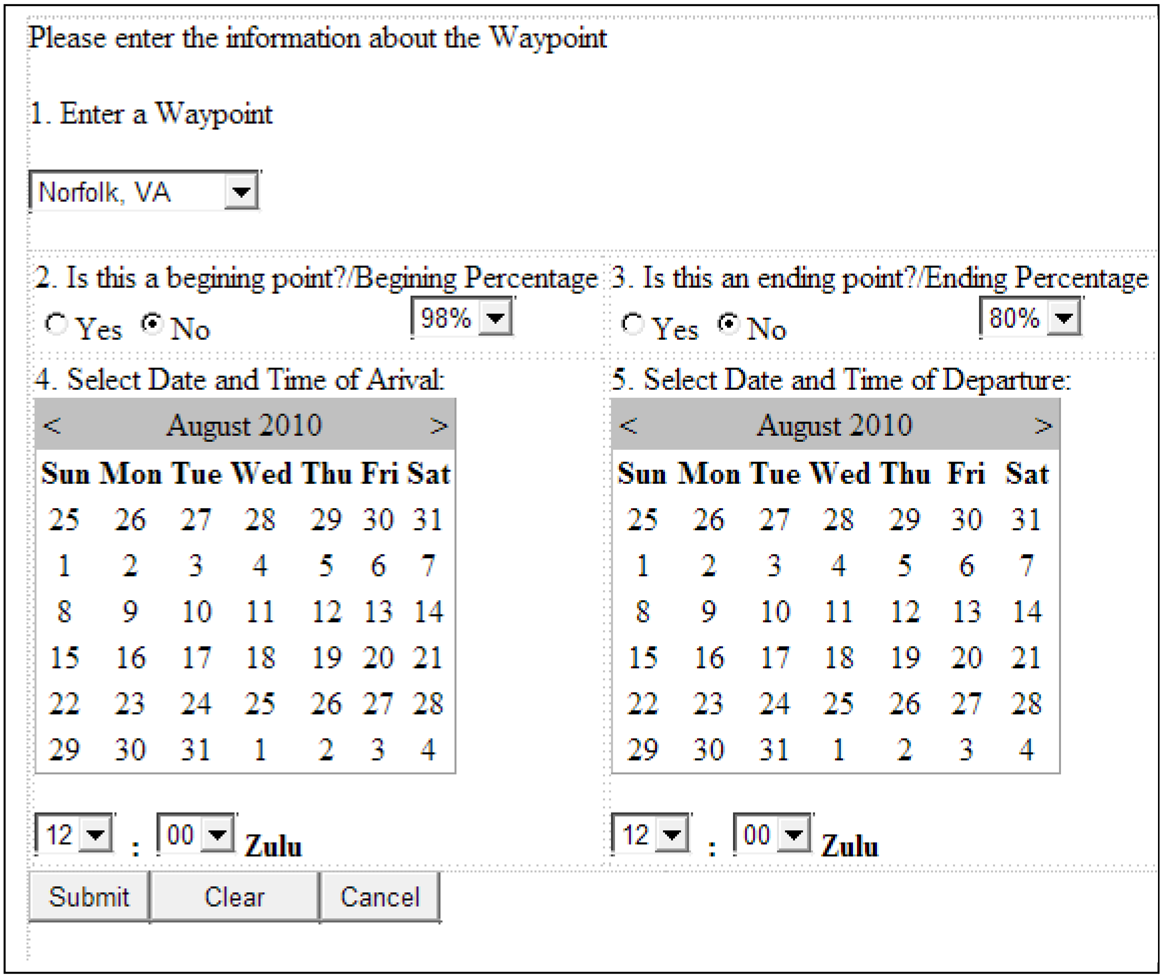

Figure 21. Example of intuitive text-based interfaces.

In Figure 21, the interface allows beginning and ending points on the plan to be entered. If the answer is "yes" to a beginning point, then the calendar and time input for arrival should be grayed out and unavailable. Likewise, if "yes" is selected for an ending point, then the calendar and time for departure should be grayed out and unavailable. If the answer is "no," then the percentages should be grayed out and unavailable. The "percent to maintain" over the entire plan should be entered when the plan is sent to the CONUS server.

B. USE-CASE DIAGRAMS

Use-case diagrams provide a means to visually describe the interaction users, or in UML terminology, actors have with a system. The following use-case diagrams offer a preliminary starting point for mocking up additional GUI views and the eventual functionality of both the NFMS and FSMD.

1. NFMS Use-Case Diagram

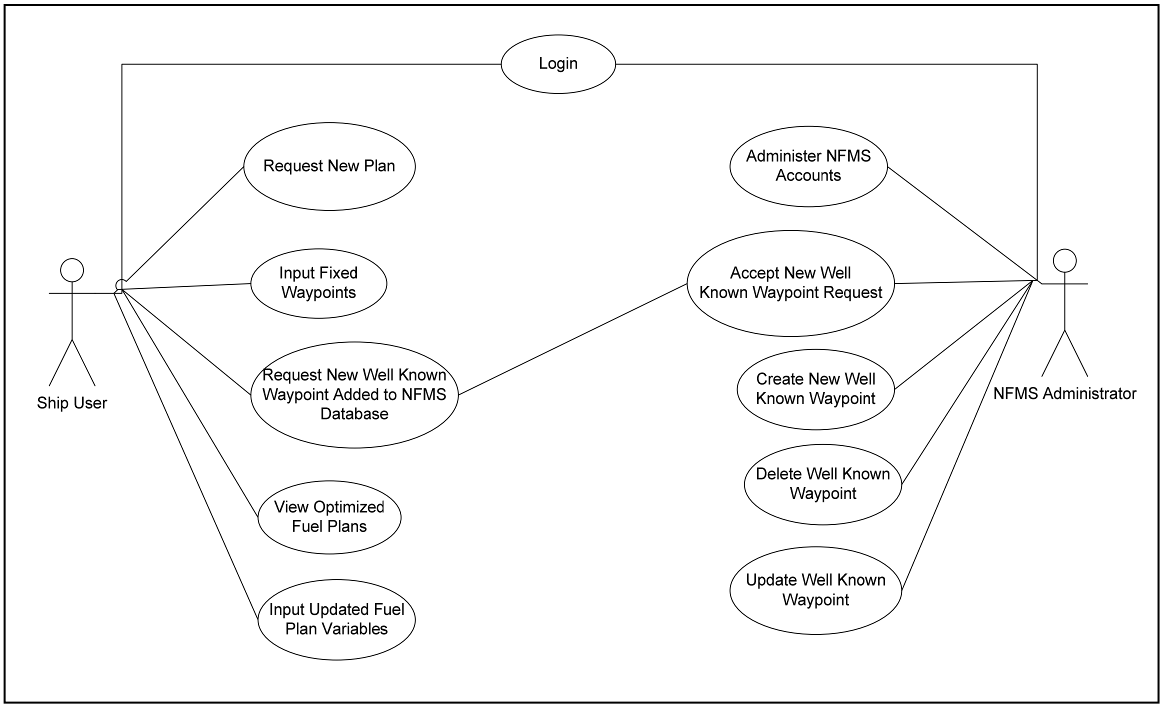

Figure 22. NFMS System Level Use-Case diagram

Figure 22 depicts the NFMS system use-case diagram. It is comprised of two actors, a user and administrator, both of whom are required to login to the system. The information flows between the servers have been described in Chapter III. Here, the different functionality is depicted through interfaces. One is requesting a new plan that will ultimately involve inputting the waypoint, the GUI for which is shown in Figure 21. If the waypoint is not already in the database, then the user will need to request a new waypoint be entered. Only an administrator should create, update and delete a well-known waypoint from the system. These well-known waypoints are the fixed waypoints described in Chapter III and the fixed nodes in the transportation network described in Chapter IV. The user can also view a plan in the system in the different views shown in Figures 19 and 20. Finally, the user will be able provided updated fuel plan variables to a plan that is in use, as described in Chapter III.

2. FSMD Use-Case Diagram

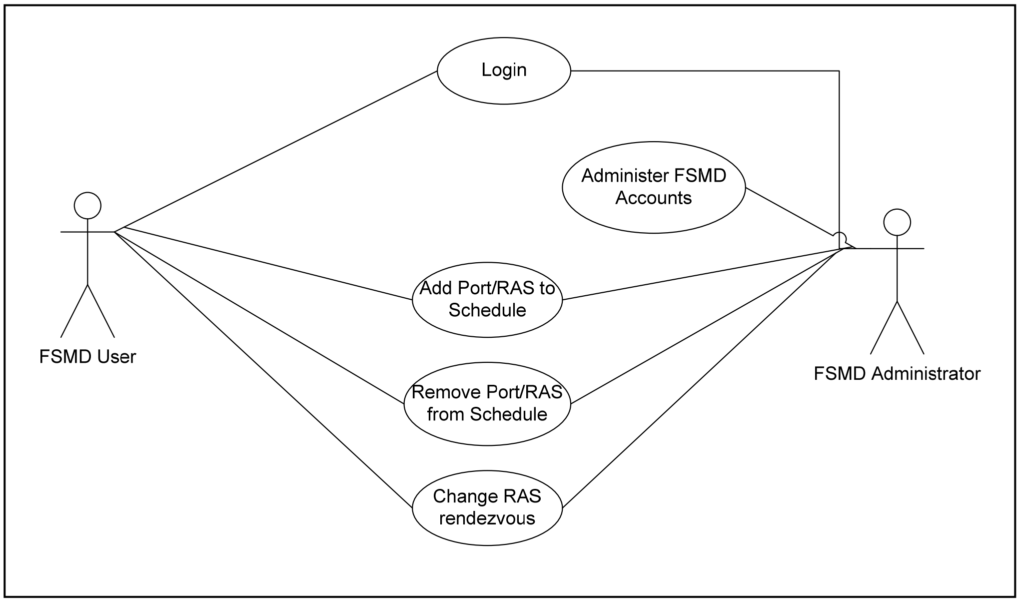

Figure 23. FSMD System Level Use-Case diagram

The FSMD is an important part of the NFMS since, without it, no alternate refueling waypoints can be discovered. Figure 23 depicts some of the user interaction with the FSMD. At the user level the Port/RAS addition, removal, or change should be for that user's particular port, ports in a region, or refueling ship. At the administrator level the addition, removal, or change in a schedule can be system wide on any of the ports or refueling ships. The ports in a region would be, for example, where the 5th Fleet is changing the availability for ports within the AOR. It would be an unnecessary risk to allow the commercial port itself to have access to the system to change their schedule. The administrator should be available to resolve any discrepancies with running a large database application. The GUIs and use-cases described in this chapter have been used to show the look and feel of NFMS.

VI. CONCLUSIONS

A. SUMMARY

We have laid out a detailed requirements analysis for an NFMS decision-support system that supports the refueling planning process. Our proof of concept shows that the NFMS can optimize refueling plans for individual Navy ships, while providing valuable decision-making alternatives in the form of tradeoff analysis not available in the current PIM system. One of the major benefits of the NFMS is that it can adapt a refueling plan to changes in the weather "on the fly," a feature beyond the capabilities of the static PIM approach. This results in more efficient usage of fuel with the commensurate benefit of reducing overall fuel usage costs. The ability to factor in the dimension of weather also enhances the "realism" of the decision support system. By providing decision makers with the ability to explore alternate scenarios, it strengthens the portfolio of choices for building refueling plans. Further, the NFMS provides a tidy circumscribed test bed that could be used as a training environment to sharpen planning and forecasting skills.

B. RECOMMENDATIONS AND FUTURE WORK

We have detailed requirements for an NFMS DSS and shown how this could, in principle, be implemented. This work could be extended in many interesting ways, a few of which we suggest below.

1. Implementing FSMD and NFMS Prototypes

A full implementation of an NFMS prototype is desirable and would require, in parallel, the development of a detailed FSMD database. Using the FNMOC route generator service and the requirements detailed in this thesis as a starting point, follow-on thesis work could implement prototypes for both the NFMS and FSMD. These efforts would require extensive knowledge of a database system such as Microsoft Access™ or SQL Server™, XML, Excel, a map-based user interface (MUI) and a programming language such as Visual Basic to coordinate the databases, the algorithms and the MUI.

The FSMD can be prototyped in conjunction with the NFMS if the interfaces are designed prior to prototyping. The requirements detailed in this thesis in the form of the tables in Chapters III and IV provide a strong foundation for designing and developing the database schema and associated tables.

2. Validation of the Model Using Simulation

Once a working NFMS has been developed, detailed validation of the model can be conducted. The spreadsheet optimization engine allows for many "what if" scenarios involving different levels of "percent to maintain" and "GTG burn fuel average"; other adjustable parameters could be added to the model as the validation procedure unfolds. An accompanying discrete event simulation could be developed using a language such as Arena™ to not only corroborate the results of the optimization model, but also to reveal possible shortcomings of the model, as well as opportunities for improvement and refinement of the model. The simulation could also be used to extend the scope from an individual ship to a CSG or ESG.

3. Add Cost to Fuel Management Database

By adding cost weights to the different refueling points, the optimization path can reflect not only the most fuel efficient, but also the most cost efficient routes as well. For example, the weight on a NATO oiler may be 1 or 2 depending on the price per barrel of DFM. However, the cost of pulling into port at Seychelles could be as large a multiplier as 9. If statistical modeling can provide accurate weights for the different refueling points, then it may prove to be less fuel efficient to go to the NATO oiler first than to pull into Seychelles and not refuel inport. This would be different from the most fuel efficient path that recommends pulling into Seychelles and refueling inport.

4. Scalability

The scenario described in Chapter IV as a proof of concept assumes a single ship planning its voyage across the ocean. However, ships normally deploy within a Carrier Strike Group (CSG) or Expeditionary Strike Group. These CSG and ESG can and do deploy with a refueling asset. There should be a function built into the NFMS that allows for a ship to be deployed with a CSG or ESG and manage the refueling plan at a higher level where the Commodore of a group or squadron can manage refueling plans for more than one ship at a time.

5. Operational Boxes (OPBOX)

As stated in the assumptions for this thesis, Navy ships do not always follow a straight line through the ocean to get from point A to point B. At times, they are given a wide area of the ocean called an OPBOX to stay inside for searching and/or monitoring purposes. Inside an OPBOX, a ship can be barely moving, may have a search pattern to follow, or could drive for winds for flight operations. Various averages of fuel consumptions should be gathered based on ship class to determine the amounts of fuel expended for these types of operations. Using this data, an OPBOX schedule can be generated to give NFMS a way of estimating the fuel burned between entering an OPBOX at a DTG and departing an OPBOX at a DTG.

NFMS can fill a gap in the planning process for Navy decision makers. The current method of determining fuel usages is based on historical data and at best the PIM model that is inaccurate. NFMS will be able to accurately predict fuel consumption for Navy ships, a great benefit to the planning and budgeting process. Then NFMS can optimize the plans based on current weather conditions or dynamically changing ship schedules, ensuring that ship operate within their budget. Also, since refueling operations will go from periodic to planned, more time can be spent on station and overworked crews do not need to expend extra energy needlessly refueling.

This thesis provides future areas of research for follow on theses. Prototyping the NFMS and its interfaces, modeling and prototyping the FSMD, and simulating "what if" scenarios using the Microsoft Excel tables is just the beginning.

THIS PAGE INTENTIONALLY LEFT BLANK

LIST OF REFERENCES

[1] Department of Defense Office of the Chief Information Officer. Global Information Grid Architectural Vision, Vision for a Net-Centric, Service-Oriented DoD Enterprise, version 1.0, June 2007. Available: http://cio-nii.defense.gov/docs/GIGArchVision.pdf (accessed 15 July 2010).

[2] Department of Defense Office of the Chief Information Officer. Defense Information Enterprise Architecture, version 1.0, April 2008. Available: http://cio-nii.defense.gov/docs/DIEAv1.pdf (accessed 15 July 2010).

[3] Department of Defense. "Chapter 7 Acquiring Information Technology, Including National Security Systems." In *Defense Acquisition Guide*. Available: https://acc.dau.mil/dag (accessed 15 July 2010).

[4] R. Hayes-Roth. "Model-based Communication Networks and VIRT: Filtering Information by Value to Improve Collaborative Decision-Making." *10th International Command and Control Research Technology Symposium*, April 2005.

[5] G. M. Marakas, *Decision Support Systems in the 21st Century 2nd Ed*. New Jersey: Pearson Education, Inc., 1999.

[6] Department of the Navy, Fleet Numerical Meteorology and Oceanography Center, *AOTSR/WEAX Software Design Description*, May 2008.

[7] Naval Sea Systems Command. "NAVSEA Incentivized Energy Conservation Program," Available: http://www.i-encon.com (accessed 15 July 2010).

[8] G. G. Brown, "Steaming on Convex Hulls." *Interfaces*, vol. 37, no. 4, pp. 342–352, July–August 2007.

[9] S. E. Dreyfus, *The Art and Theory of Dynamic Programming*. New York: Academic Press, 1977

[10] Naval Sea Systems Command. "Shipboard Energy Conservation Guide," April 2009. Available: http://www.i-encon.com/ENCON%20Guide%202010.pdf (accessed 2 August 2010).

[11] A. A. Montes, "Network shortest path application for optimum track ship routing," Master's thesis, Naval Postgraduate School, Monterey, CA, 2005.

THIS PAGE INTENTIONALLY LEFT BLANK

INITIAL DISTRIBUTION LIST

1. Defense Technical Information Center
   Ft. Belvoir, Virginia

2. Dudley Knox Library
   Naval Postgraduate School
   Monterey, California